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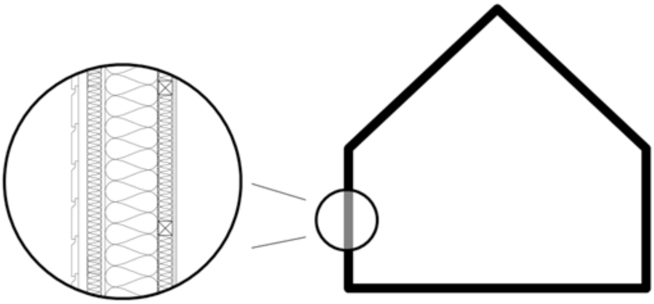
Björn Berggren

Division of Energy and Building Design
Department of Architecture and Built Environment
Lund University
Faculty of Engineering LTH, 2013
Report EBD-T--13/16



Lund University

Lund University, with eight faculties and a number of research centres and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 112 000 inhabitants. A number of departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 6 000 employees and 47 000 students attending 280 degree programmes and 2 300 subject courses offered by 63 departments.

Division of Energy and Building Design

Reducing environmental effects of construction and facility management is a central aim of society. Minimising the energy use is an important aspect of this aim. The recently established division of Energy and Building Design belongs to the department of Architecture and Built Environment at the Lund University, Faculty of Engineering LTH in Sweden. The division has a focus on research in the fields of energy use, passive and active solar design, daylight utilisation and shading of buildings. Effects and requirements of occupants on thermal and visual comfort are an essential part of this work. Energy and Building Design also develops guidelines and methods for the planning process.

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Licentiate Thesis

Keywords

Net Zero Energy Building, passive house, thermal bridge, building envelope, energy performance, moisture performance, multi criteria decision making, climate change, climate scenarios, EN ISO 13789, EN ISO 10211

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Abstract

Buildings account for a significant proportion of the energy use that generates greenhouse gases and consequently drives the ongoing climate change. As the population of the world increases, the need for buildings increases, while the energy use needs to decrease. A reduction in energy use and increased use of renewable energy are important measures for climate change mitigation. A first step in decreasing the energy use of a building in a Nordic climate is to increase the thermal resistance of the building envelope.

The combination of climate change and more insulation in building elements will result in a different microclimate within the building elements. External parts in well-insulated building envelopes will have a microclimate more similar to the exterior climate as the thermal resistance increases and moisture may take a longer time to dry out.

Today, there are several established ways to calculate and quantify the energy performance of buildings and building components. As regards calculation of transmission heat transfer through building envelopes, there is a lack of knowledge among Swedish engineers and architects. There are ambiguities regarding the definition of a thermal bridge and the way building elements are quantified in energy calculations.

There are models to quantify the moisture performance of a building element, where the focus is to evaluate the risk of mould growth. Regarding other moisture-related problems, such as corrosion, deformations etc., critical moisture levels are established. However, these levels are not valid for short-term loads. Only models of mould growth take into account fluctuations in hygrothermal conditions.

Traditionally, durability and robustness of building elements are based on experience and are not specified in quantitative terms. However, increasing the thermal resistance in combination with climate change will result in different hygrothermal conditions within the building envelope. Building elements needs to be designed with reference to these aspects.

To enable evaluation of energy- and moisture performance, which are presented in dissimilar units, a model has been developed in order to present a weighted value which includes both aspects. The model includes

a performance failure indicator that ensures that the weighted value of an evaluation is unacceptable if any of the evaluated indicators are below acceptable level. This means that it is not possible to compensate for the poor performance of one indicator by achieving a very high value for another indicator.

Initial tests have been conducted by using the model to evaluate a limited part of a building envelope, but also for a whole building. The tests of the model showed that it is possible to handle a large set of criteria and to weight them into one value.

Future work in this project will investigate building envelopes in order to indicate measures that could have a large effect on the transmission heat transfer losses. Furthermore, additional work to investigate future climate scenarios and improvement of the usability of the model will be performed.

Contents

Nomenclature

A	Area
A_C	Conditioned area
A_i	Area of building element, i
CHP	Combined heat- and power plant
c_i	Charging energy of carrier, i, to storage
d_i	Delivered energy of carrier, i, from the grid
dc_i	Discharge energy of carrier, i, from storage
DE	Demolition energy
e	Subscript indicating external measurement
E_C	Energy consumed on site for construction of building
E_D	Energy used for demolition of building
EE	Embodied energy
EE_i	Initial embodied energy
EE_r	Recurring embodied energy
e_i	Exported energy of carrier, i
E_{OA}	Annual operating energy
EP	Energy performance
EPR	Energy Payback Ratio
EPT	Energy Payback Time
E_R	Energy that will be recycled or extracted
E_{TC}	Energy used for transportation on and off site during construction phase
E_{TW}	Energy used for transportation of waste materials off site after demolition
F_a	Conversion factor for λ due to aging
f_{grid}	Grid interaction
f_{load}	Load match
F_m	Conversion factor for λ due to moisture
F_T	Conversion factor for λ due to temperature
f_T	Temperature conversion coefficient
f_u	Moisture conversion coefficient, mass by mass
f_ψ	Moisture conversion coefficient, volume by volume
g_i	Generation of energy carrier, i

H_A	Transmission heat transfer coefficient to adjacent buildings
H_D	Direct heat transfer coefficient
H_g	Steady state ground heat transfer coefficient
H_T	Transmission heat transfer coefficient
H_U	Transmission heat transfer coefficient through unconditioned spaces
i	Subscript indicating internal measurement
k	Permeability of insulation
$k(a)$	Performance failure indicator for alternative a
l_i	Load of energy carrier, i
l	Length
L_b	Life span of building
LCE	Life Cycle Energy
L_{mi}	Life span of material, i
L_{2D}	Thermal coupling coefficient from a 2-D calculation
L_{3D}	Thermal coupling coefficient from a 3-D calculation
m_i	Quantity of building material, i
M_i	Energy content of the material, i
MCDA	Multi Criteria Decision Analysis
MCDM	Multi Criteria Decision Making
NER	Net Energy Ratio
Net ZEB	Net Zero Energy Building
Net ZEC	Net Zero Energy Cluster of buildings
OE	Operating energy
oi	Subscript indicating overall internal measurement
PV	Photovoltaic
Ra_m	Rayleigh number
RES	Renewable Energy Sources
RH	Relative humidity
RH_{crit}	Relative humidity, critical conditions
ST	Solar thermal
T	Temperature
T_e	External/outdoor temperature
$T_{\bar{e}, daily}$	Daily average of external/outdoor temperature (°C)
$T_{\bar{e}, monthly}$	Monthly average of external/outdoor temperature (°C)
$T_{\bar{e}, 24h}$	24-hour running average external/outdoor temperature (°C)
T_i	Internal/indoor temperature
t_{mp}	Response time for initial stages of mould growth on pine sapwood
t_{ms}	Response time for initial stages of mould growth on spruce sapwood
t_{vp}	Response time for visual appearance of mould growth on pine sapwood

t_{vs}	Response time for visual appearance of mould growth on spruce sapwood
U	Thermal transmittance
u	Moisture content, mass by mass
v	Moisture content by volume
$V(a)$	The total value of investigated alternative *a*
v_e	Moisture content, by volume, of external air
v_i	Relative value for criterion *i*
v_s	Vapour content, by volume, at saturation for the temperature T
w_i	Weighting factor for criterion *i*
WD	Weighted Demand
WS	Weighted Supply
Z	Resistance to moisture flow
ZEB	Zero Energy Building
ΔEE	Annual difference of embodied energy due to a specific measure
ΔEE_T	Total difference of embodied energy due to a specific measure
ΔOE	Annual difference of operating energy due to a specific measure
ΔOE_T	Total difference of operating energy due to a specific measure
$\Delta\nu$	Local moisture supply
β	Relative use of electricity
ξ	Relative temperature factor
λ	Thermal conductivity
χ	Point thermal bridge
ψ	Moisture content, volume by volume
Ψ	Linear thermal bridge
θ	Temperature

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I would like to thank all members of the SBUF reference and all participating experts within the international project: IEA SHC Task40/ECBCS Annex 52: “Towards Net Zero Energy Solar Buildings”. All have, without prestige, shared their knowledge and expertise.

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Lund, April 2013
Björn Berggren

Sammanfattning

Byggsektorn står för en betydande del av energianvändningen och energianvändningen generar växthusgaser som driver på klimatförändringar. Eftersom jordens befolkning ökar, ökar behovet av byggnader, samtidigt som energianvändning inom byggsektorn behöver minska. En minskning av energianvändningen och ökad tillförsel av förnybar energi i världens bebyggelse ses som en viktig åtgärd och strategi för att minska utsläppen av växthusgaser.

Ett första steg för att minska energibehovet för uppvärmning i byggnader i ett nordiskt klimat är att utforma dem med välisolerade klimatskal.

Kombinationen av klimatförändringar och mer välisolerade byggnadsdelar kommer att innebära att mikroklimatet i byggnaders klimatskal förändras. Yttre delar i välisolerade klimatskal kommer att få ett mikroklimat som är mer likt utomhusklimatet och det kommer ta längre tid för fukt att torka ut jämfört med mindre välisolerade byggnadsdelar.

Det finns idag flera olika etablerade sätt att beräkna och presentera energiprestanda för hela byggnader och för byggnadsdelar. Det finns dock kunskapsbrist bland svenska ingenjörer och arkitekter när det gäller att beräkna energiförluster genom byggnaders klimatskal. Det råder oklarheter om hur en köldbrygga definieras samt hur byggnadsdelar ska kvantifieras för energiberäkningar.

Det finns modeller för att kvantifiera en byggnadsdels fuktprestanda där fokus är att utvärdera risken för mögelpåväxt. Även för andra fuktrelaterade problem, exempelvis korrosion, rörelse, deformationer etc. finns det etablerade kritiska fuktnivåer. Dessa gäller dock inte vid kortvarig belastning. Det är enbart modellerna för mögelpåväxt som tar hänsyn till fluktuerande tillstånd.

Ofta baseras bedömningar av byggnadsdelars kvaliteter på erfarenheter. Man använder tumregler och gör ”som man alltid har gjort”. I och med att klimatförändringarna kommer att ge oss ett mer extremt klimat och att mer isolering förändrar förutsättningarna behöver våra byggnadsdelar utformas för att ta hänsyn till dessa aspekter.

För att sammanväga fukt- och energiprestanda, som redovisas med olika enheter, har en modell tagits fram för att kunna presentera ett prestandatal för byggnad eller byggnadsdel som inkluderar båda aspekterna. Modellen innehåller en prestandafaktor som säkerställer att det sammanvägda resultatet av en utvärdering visar att det är oacceptabelt om någon av de utvärderade indikatorerna är under acceptabel nivå. Detta innebär att det inte är möjligt att överkompensera ett undermåligt resultat för en indikator genom att uppnå mycket högt värde för en annan indikator.

Inledande tester av modellen har genomförts för att utvärdera en begränsad del av ett klimatskal och en hel byggnad. Testerna visar att det är möjligt att hantera ett stort antal indikatorer och sammanväga dem till ett prestandatal.

Fortsatt arbete inom detta projekt kommer att undersöka olika klimatskal för att finna åtgärder som kan ge stora förbättringar avseende värmemotstånd. Mer studier av framtida klimatscenarion samt arbete för att öka användbarheten av den framtagna utvärderingsmodellen kommer att genomföras.

List of articles

Conference proceedings

I Berggren, B., & Wall, M. (2011a). The importance of a common method and correct calculation of thermal bridges. Proceedings from *9th Nordic Symposium on Building Physics*, pp 977-984. Tampere, Finland.

II Berggren, B., Stenström, H., & Wall, M. (2011). A parametric study of the energy and moisture performance in passive house exterior walls. Proceedings from *4th Nordic Passive House Conference*, Helsinki, Finland

III Berggren, B., & Wall, M. (2011b). Thermal bridges in passive houses and nearly zero-energy buildings. Proceedings from *4th Nordic Passive House Conference*, Helsinki, Finland.

IV Berggren, B., & Wall, M. (2012a). Hygrothermal conditions in exterior walls for passive houses in cold climate considering future climate scenario. Proceedings from *5th Nordic Passive House Conference*, Trondheim, Norway.

V Berggren, B., & Wall, M. (2012b). Moisture Conditions in Exterior Walls for Net Zero Energy Buildings in Cold Climate Considering Future Climate Scenario. Proceedings from *7th International Cold Climate HVAC Conference,* Calgary, Canada.

Peer reviewed journals

VI Berggren, B., & Hall, M. (2013). LCE analysis of buildings - Taking the step towards Net Zero Energy Buildings. *Energy and Buildings, 62 (0). 381 - 391.* http://dx.doi.org/10.1016/j.enbuild.2013.02.063

VII Berggren, B., Wall, M., Flodberg, K., & Sandberg, E. (2013). Net ZEB Office in Sweden - a case study, testing the Swedish Net ZEB definition. Accepted for publication (2013-05-13) in *International Journal of Sustainable Built Environment.*

VIII Berggren, B., & Wall, M. (2013). Calculation of thermal bridges in (Nordic) building envelopes – risk of performance failure due to inconsistent use of methodology. Submitted, in revised form (2013-05-13) to *Energy and Buildings*.

1 Introduction

This chapter gives an overview of energy and environmental issues worldwide and within the Nordic countries. Furthermore, it presents the aim and scope of the study, the methodology and the structure of this thesis.

1.1 Background

1.1.1 Energy and environmental issues

One of the greatest challenges of the world is to reduce greenhouse gas emissions and to secure assets for energy. Energy use in buildings worldwide accounts for over 40% of primary energy use and 24% of greenhouse gas emissions (International Energy Agency, 2011). The building sector is expanding. Therefore, reduction of energy use and the use of energy from renewable sources in the buildings sector constitute important measures required to reduce energy dependency and greenhouse gas emissions.

The Intergovernmental Panel on Climate Change, IPCC, was founded in 1988. IPCC has delivered four of the most comprehensive scientific reports about climate change produced worldwide, the Assessment Reports. A fifth report is under way, expected in 2013/2014. The most recently published report, AR4 states through observations and measurements, unambiguously, that there is a warming of the climate system (IPCC, 2007).

The increase in temperature is larger at northern latitudes but is widespread all over the globe. The report further concludes that precipitation has increased significantly in the eastern parts of North and South America, northern Europe and northern and central Asia. The increases in the sea levels are consistent with the warming mainly due to thermal expansion of the oceans and the shrinking of glaciers. On all continents significant changes in physical and biological systems have been observed. Depending on continent; 89-100% of the observed changes are consistent with warming.

In order to try to explain the climate change, IPCC has used 19 different models to simulate temperature changes all over the globe and compared the results with observations for the period 1906-2000. The results show that models using only natural forcing cannot explain the temperature changes, while models using both natural and anthropogenic forcing show much better agreement with observations. The changes in concentration of aerosols and Green House Gases (GHG) in the atmosphere, solar radiation and land cover alter the balance of the globe's climate system and are drivers of climate change. Annual global GHG emissions have increased by 70% between 1970 and 2004. Annual emission of carbon dioxide (CO_2), the most important GHG, has grown by about 80% during the same period.

Based on the IPCC Special Report on Emission Scenarios, SRES, (IPCC, 2000) climate change has been projected for the 21st century. For the next two decades a warming of about 0.2°C per decade is projected for most of the SRES scenarios. Even with the most optimistic scenario, representing a world more integrated and more ecologically friendly, the temperature is estimated to increase by 1.8°C and the sea level is expected to rise 0.18-0.38 m by the end of the 21st century.

More than 100 countries adopted a global warming limit of 2°C at the Conference of the Parties' fifteenth session, COP 15, in Denmark 2009 (UNFCCC, 2010). To keep the warming below 2°C was declared essential. If the temperature increases by more than 2°C more than 2.5 billion people risk to be exposed to water shortage by 2080 (Parry et al., 2001). Furthermore, it is likely that it will lead to some impacts that are irreversible, such as coastal flooding and extinction of species (IPCC, 2007).

To reduce the energy use in buildings, the European Parliament, EU, has introduced a legal framework to work within all member states; Directive 2010/31/EU on the energy performance of buildings (European parliament, 2010).

The directive states that all member states shall ensure that by 31 December 2020, all new buildings are nearly zero-energy buildings, which means that they must have a very high energy performance and the nearly zero amount of energy required, should be covered to a very significant extent by renewable energy. The directive also states that buildings that undergo major renovation shall be upgraded to meet a minimum level of energy performance set by the member state. Major renovation may be defined as renovation of a building where the cost is higher than 25% of the value of the building or if more than 25% of the building envelope undergoes renovation. By the year 2013, at the latest, member states shall adopt and publish laws and regulations to comply with the directive.

Sweden has an environmental policy. This is based on goals defined within 16 environmental quality objectives adopted by the Swedish Parliament in 1999 and revised in 2005. The goals describe a desired quality and condition of the Swedish environment. In November 2005 the Swedish parliament adopted 72 interim targets to concretize the work towards reaching the goals. Up until 2012, one of the interim targets, within the main objective called "A Good Built Environment", applied to energy use in buildings (Marszal et al., 2010a):

> "Total energy consumption per unit area heated in residential and commercial buildings will decrease, with target reductions of 20% by 2020 and 50% by 2050, compared with consumption in 1995. By 2020 dependence on fossil fuels for the energy used in the built environment sector will be broken, at the same time as there will be a continuous increase in the share of renewable energy."

However, in 2012 the target was slightly redefined. The target is now defined as Sweden strives towards 20% more efficient energy use within buildings by 2020 and 50% more efficient energy use by 2050 (Ministry of Environment, 2012).

1.1.2 Moisture related damage in building envelopes

Enhancing the energy performance of the building envelope by means of improved air tightness and increased thermal resistance by increasing the amounts of insulation, is frequently introduced in order to achieve a lower energy demand for buildings, both for renovation and new buildings. However, increased thermal resistance of the building envelope will result in a different microclimate within the building envelope. For example, the outer parts of a wall will have hygrothermal conditions more similar to the exterior climate and moisture may take longer time to dry out. A parametric study carried out in Norway (Geving & Holme, 2010) showed that increased amounts of insulation resulted in increased relative humidity in the constructions during winter. This may give a higher risk of moisture related performance failure.

A Swedish study showed that cold attics already suffer from high humidity levels and mould growth (Ahrnens & Borglund, 2007). These problems may already appear in roof constructions with amounts of insulation which may be considered as standard amounts, 400 mm (Samuelsson, 2008).

Severe moisture problems have also been discovered in walls with wooden framing and Exterior Insulation and Finish Systems, EIFS, which is a type of exterior wall plaster system applied on insulation. EIFS requires that both rain seal and air seal are located in one layer in the outer part of the wall, often called single-stage sealing. The system was originally developed in Germany in the 1950s and 1960s to improve the energy performance of old masonry houses. During the oil crisis in the early 1970s, contractors in Sweden started to use EIFS to improve external wall constructions of brick and lightweight concrete, and the results were good (Elmarsson, 1979). During the 1980s the system was also implemented into constructions for new buildings, with wooden framing. The risk of moisture damage in an undrained wall with organic material was not fully considered. EIFS, which worked well in combination with non-organic wall constructions, were not suitable in combination with organic constructions (Samuelsson, Mjörnell, & Jansson, 2007).

1.1.3 The need for assessment of building envelopes considering energy efficiency and moisture safety using a life-cycle perspective

The type of damage described above is widespread in Sweden and illuminates moisture related damage which is the result of implementation of new techniques and materials in constructions, without performing tests or a thorough analysis.

Today, it is generally alleged in Sweden that energy use in the operational phase of a building accounts for 85% of energy used during its life cycle. This refers to studies conducted in the late 1990s (Adalberth, 2000). On the basis of the recast of the energy directive, one may assume that efforts to improve buildings' energy performance will be taken by several stake holders in many countries within a near future, resulting in a reduction of energy used during the operational phase. Therefore the energy needed for production of buildings will become more important in relative terms.

It can be concluded that there is a need to develop robust building envelopes that can meet future demands for energy efficiency throughout their life cycle where moisture safety is valued as an important factor in the evaluation and where a future climate scenario is considered. This is due to expected improvements in the energy performance of buildings together with identified risks related to increased thermal resistance of the building envelope.

1.2 Objective and scope of the study

1.2.1 Hypothesis and objective

The hypothesis behind this research project is:

- The new energy directive will lead to a need of increased thermal resistance in building envelopes, both in new construction and renovation.
- Because of climate change, building envelopes will face new boundary conditions.
- The combination of increased thermal resistance and new boundary conditions will change the hygrothermal conditions within building envelopes in a near future. This may have the result that technical solutions and principles, by history confirmed as best practice, may suffer from moisture related damage.

The objective of this research is to identify a methodology to evaluate building envelopes, taking energy and moisture performance into consideration. These two requirements sometimes come into conflict with each other. Therefore, the methodology should make it easier for building owners to take informed decisions regarding their buildings for the entire life cycle. The results of the research are aimed at consultants, contractors and building owners.

1.2.2 Scope

The licentiate thesis presents a method for evaluation of new building envelopes and renovation measures for building envelopes with reference to moisture safety and energy performance.

The methodology is intended to be used both for renovation and new construction. Different evaluation methodologies are studied and parameters that need to be part of the decision making are investigated. The studied parameters are:

- Energy performance of buildings, focusing on transmission heat transfer through the building envelope. When higher quantities of insulation are used, decreasing the transmission heat transfer, the relative share of thermal transmittance and the importance of thermal bridges increases. This is investigated in papers I, III, and VIII.
- Embodied energy. As buildings use less energy during building operation, the relative share of embodied energy increases. Hence, choosing

different materials for the building envelope requires more knowledge about the embodied energy. An investigation of different methodologies, databases and future impact was conducted, presented in paper VI.
- Net Zero Energy Buildings, Net ZEBs. The concept was studied in order to understand today's best practice and what technical solutions it may require. This is investigated in papers VII.
- Risk of performance failure due to moisture. Different models for onset of mould growth and the possible effects of increased thermal resistance in building envelopes were studied in papers II, IV and V.
- Future climate scenarios. Studies indicate increased precipitation, wind and temperature. This will affect the hygrothermal conditions within building envelopes. Future climate scenarios and possible effects were studied in papers IV and V.

The research has partly been carried out within the international project IEA SHC Task 40/ECBCS Annex 52; Towards Net Zero Energy Solar Buildings. This project involves researchers and practitioners from 19 countries within the framework of the International Energy Agency. The project started in 2008 and ends in 2013.

1.2.3 Limitations

This research focuses on building envelopes for residential buildings in a Nordic climate, focusing on the north European countries; Denmark, Finland, Norway and Sweden.

The developed evaluation method does not claim to be able to judge whether a design will or will not withstand future climate. It will primarily be suitable for comparing energy performance and moisture safety between different technical solutions.

1.3 Methodology

A literature review was conducted to investigate how energy performance and moisture conditions may be calculated today. Since transmission heat transfer losses may be calculated differently, a web based questionnaire was conducted among Swedish engineers and architects. Based on the questionnaire, studies were made regarding possible performance failure scenarios due to misunderstandings and misinterpretations that may occur.

Critical levels for changes in building materials and models for onset of mould growth were reviewed. Future boundary conditions, focusing on outdoor climate and climate change were investigated.

In order to gather knowledge and experience of the different calculations and evaluation methodologies, various case studies were conducted during the project. The case studies focused on possible lateral effects of increased amounts of insulation and more energy efficient buildings considering a future climate scenario.

Also, publications concerning climate change and Multi-Criteria Decision-Making, MCDM, were reviewed. A method to evaluate energy and moisture performance, based on MCDM, was developed. The method was tested by conducting hygrothermal and energy simulations a limited part of a building envelope and also for a whole building. The results from the simulations were converted into performance criteria and used as input data for the model.

1.3.1 Simulations

The thermal transmittance for building elements and thermal bridges was calculated using HEAT 2.8 and HEAT 3.6 (Blocon Sweden, 2008). HEAT is a computer program for two- and three-dimensional transient and steady-state heat transfer calculations. The program is validated against the standard EN ISO 10211.

Hygrothermal simulations were conducted using the numerical computer program WUFI (Fraunhof-Institut fur Bauphysik, 2013). WUFI is a program designed to calculate hygrothermal processes. It includes 1D or 2D coupled heat and moisture transport, and considers both vapour diffusion and capillary conduction.

Simulations to determine energy demand were conducted by using IDA Indoor Climate and Energy 4.5, IDA ICE (EQUA, 2013). IDA ICE is a dynamic multi-zone simulation computer program which calculates thermal indoor climate and energy use of a whole building.

1 .4 Contents and outline of the thesis

This introductory chapter presents a background to the challenges the building sector is facing regarding climate change and the need to reduce the environmental impact of buildings. The principal objective and scope of the study is defined and the method is presented.

Chapter 2 reviews the relevant theoretical basis and the state of the art regarding energy and moisture performance, future climate scenarios and MCDM.

Chapter 3 presents the model for evaluation which may be used to weight performance indicators for moisture performance and energy performance.

Chapter 4 presents tests of the model, both for a limited part of a building envelope, and also for a whole building.

Chapter 5 presents discussion and conclusions based on the literature review and the test of the model. Furthermore it summarises research questions which may be addressed in the continuation of this work and further use of the model.

2 Theory – State of the art

In this section, the basis for calculations, simulations and evaluation of energy- and moisture performance is presented. Relevant boundary conditions for the calculations and simulations are summarised. Future climate scenarios and Multi-criteria decision-making, MCDM, are introduced.

2.1 Energy performance

Calculation methodologies and energy performance of buildings were studied in Papers I, II, III, VI, VII and VIII.

2.1.1 Legal requirements regarding energy performance for residential buildings in Denmark, Finland, Norway and Sweden

Adopted in December 2002, the Energy Performance of Buildings Directive, EPBD, stated that all Member States within EU shall set minimum energy performance requirements that include the amount of energy actually consumed or estimated to meet the needs associated with a standardised use of a building (European Parliament, 2003). Henceforth in this thesis, annual operating energy use, *OE*, divided by conditioned area, A_C, for buildings is referred to as energy performance, *EP* (kWh/m^{2}a).

The requirements regarding energy performance are different in the north European countries of Denmark, Finland, Norway and Sweden (Boverket, 2011; Erhvervs- og Byggestyrelsen, 2010; Statens bygningstekniske etat, 2010; Ympäristöministeriö, 2012). All countries set requirements for the energy performance (kWh/m^{2}a). Denmark, Norway and Sweden set the requirements in delivered energy. In Finland, the requirement is set as weighted energy, using weighting factors defined in the Finnish building regulations. This may be considered as requirements in primary energy.

Denmark, Finland and Norway require calculations to verify the requirements and in Sweden it is stated that the requirements should be verified partly by calculation and partly by measuring the energy consumption in the finished building.

There is no differentiation regarding the requirements on energy performance for different geographical positions within the country in Denmark, Finland and Norway. In Denmark annual average outdoor temperature and degree days are similar regardless of where in Denmark one is (excluding Greenland). In Finland and Norway, it is specified in the building codes that energy calculations are to be carried out with a specific outdoor climate, in Finland; Helsinki-Vanda, and in Norway; Oslo. Hence, no need for differentiation.

In Sweden, where the energy performance should be partly verified by measurement, and where outdoor temperatures and degree days vary greatly, the requirement is differentiated into three different climatic zones as presented in Figure 2.1.

Figure 2.1 *Swedish climate zones*

In Finland and Norway, all *OE* to the building is included in the energy performance In Sweden and Denmark the *OE* for household purposes, such as plug loads and lighting, is excluded in the energy performance requirements.

In Denmark and Norway, the energy performance requirements for residential buildings are adjusted with a factor that allows small buildings to have a higher energy performance indicator (kWh/m^{2}a). Six different categories of residential buildings are defined in Finland (plus four additional definitions for log houses, not addressed here). In Sweden the requirements on energy performance for residential buildings are not differentiated according to size or type of building. The requirements in Denmark, Finland, Norway and Sweden are summarised in Table 2.1. In Sweden the requirement is tightened by 35 kWh/m^{2}a, if electricity is used for space heating and domestic hot water.

Table 2.1 Summary of requirements regarding energy performance in Denmark, Finland, Norway and Sweden

		Denmark	Finland	Norway	Sweden Climate zone		
					I	II	III
Energy requirements for multi-family houses [kWh/m^{2}a]		52,5 + 1650/A_C	130	115	130	110	90
Energy requirements for terrace houses [kWh/m^{2}a]		52,5 + 1650/A_C	150	115	130	110	90
Energy requirements for detached single-family houses [kWh/m^{2}a]		52,5 + 1650/A_C	A_C<120; 204 120<A_C<150; 372-1.4A_C 150<A_C<600; 173-0.07A_C A_C>600; 130	120 + 1600/A_C	130	110	90
Type of energy [Delivered/Primary/Weighted]		Delivered	Weighted	Delivered	Delivered		
Energy included in the energy requirement [Yes/No]	Energy for heating	Yes	Yes	Yes	Yes		
	Energy for domestic hot water	Yes	Yes	Yes	Yes		
	Auxiliary energy for the building	Yes	Yes	Yes	Yes		
	Energy for household purposes	No	Yes	Yes	No		
Mandatory to perform energy calculations [Yes/No]		Yes	Yes	Yes	Yes		
Climate for energy calculations		Location specific	Helsinki/ Vanda	Oslo	Location specific		

2.1.2 Common indicators of energy assessment in environmental indicator systems

Today, several environmental indicator systems and certifications exist for buildings. Common ones used in Sweden are; “Miljöbyggnad”, Green Building, Breeam and Leed, managed by the Swedish Green Building Council (Swedish green building council, 2012).

Several others exist , e.g. “Miljöanpassat byggande – Göteborg” (Göteborgs stads fastighetskontor, 2009), Miljöbyggprogram SYD (Malmö stad, Lunds kommun, & Lunds Universitet, 2012), Svanen (Nordisk miljömärkning, 2012) and the Swedish criteria for passive houses (Sveriges Centrum för Nollenergihus, 2012). All these environmental indicator systems have requirements on energy performance. Within the Swedish ones, the maximum peak load for space heating is also set.

2.1.3 Net Zero Energy Buildings

The original intention of the revision of the EPBD was: *“All buildings built after 31 December 2018 will have to produce as much energy as they consume on-site”* (European Parliament, 2009). However, the final revision established ”nearly zero energy buildings” as the building target.

In Sweden, there is a definition available defined by a non-governmental organisation (Sveriges Centrum för Nollenergihus, 2012), defining a building which produces as much energy as it consumes. The balance concept of the definition is presented in Paper VII, testing the Swedish definition for an office building. Important aspects of defining zero-energy buildings have also been presented in the Swedish trade journal; Bygg och Teknik (Berggren, Wall, Karlsson, & Widén, 2012).

Today, there are an increasing number of so called zero-energy buildings (ZEBs), demonstration projects promoting a solution for reduction of energy consumption and mitigation of CO_2 emissions within the building sector. A large number of case studies has been documented by the international joint research task; IEA SHC Task 40/ECBCS Annex 52 (International Energy Agency (IEA), 2013).

There is today no international standard or building code defining the ZEB concept. The lack of commonly agreed ZEB definition has been identified by the IEA Task which has defined it as one of their main objectives to develop a common understanding and a harmonized international definition framework. The key findings and definitions developed and published within the Task so far are presented in this chapter.

In the existing literature the concept of buildings with a zero energy balance is described by a wide range of terms and expressions. Three main concepts and definitions may be distinguished:

- Zero Energy Building, *ZEB*:
  A building where renewable energy generation covers the energy use. The building is autonomous and does not interact with any external energy supply system such as district heating, gas pipe network, electricity or similar.
- Net Zero Energy Buildings, *Net ZEBs*:
  A building where renewable energy generation covers the energy use. The building interacts with an energy supply system and can export energy when the building's system generates a surplus and import energy when the building's system does not produce the quantities of energy required.
- Net Zero Energy Clusters, *Net ZECs*:
  A cluster of buildings, more than one, where the buildings interact with each other. Renewable energy generation covers the energy use within the cluster.

The autonomous, off-grid *ZEB* concept has not gained any large international attention and is rather perceived as one of the intermediate steps on the path towards grid connected *Net ZEBs* (Marszal et al., 2011). Therefore, the focus in this section is the definition and calculation methodologies for *Net ZEB* which also may be applied on *Net ZEC*.

To reach the balance of *Net ZEB* one should always start by applying energy efficiency measures to a building to reduce the energy demand. This should be followed by dimensioning and installing an energy supply system to generate energy, usually electricity, exploiting renewable energy sources, *RES*, on-site. The concept is graphically presented in Figure 2.2.

There are many different design strategies for energy efficient buildings, e.g. the Energy triangle, the IBC Energy Design Pyramid (Andresen, Kleiven, Knudstrup, & Heiselberg, 2008), the Kyoto Pyramid Passive energy design process (Dokka & Hermstad, 2006) or the Passive house design principle (Janson, 2010). The common first fundamental step in these different design strategies is to reduce the energy demand. In a Nordic climate, this is achieved by constructing an airtight and well insulated building envelope in combination with balanced ventilation with high system heat recovery efficiency.

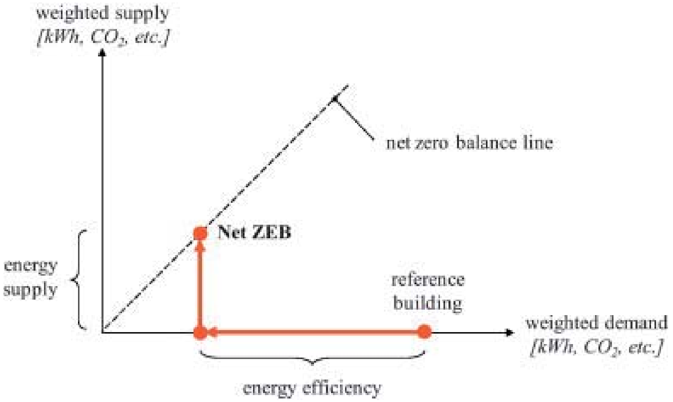


Figure 2.2 *Graph representing the Net ZEB balance concept (Sartori, Napolitano, & Voss, 2012)*

The sketch shown in Figure 2.3 gives an overview of the relevant terminology addressing the energy use in buildings and the connection between buildings and energy grids. The building's load refers to the energy demand. The energy demand may not match the delivered energy due to self-consumed on-site generation.

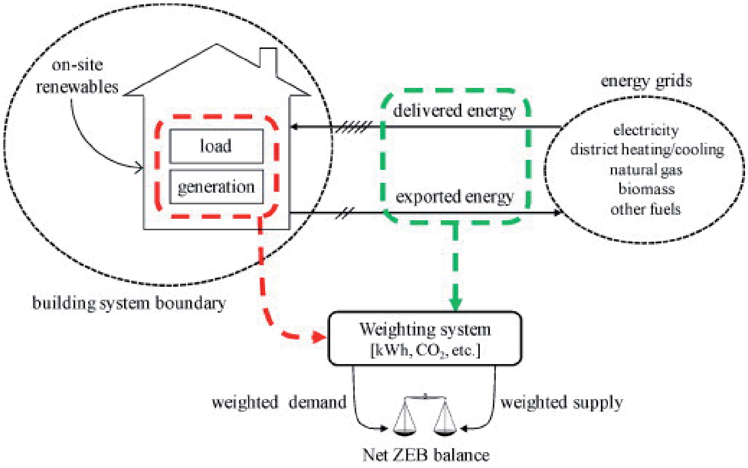


Figure 2.3 *Connection between building and energy grid (Sartori, Napolitano, & Voss, 2012)*

There are several different definitions of *Net ZEBs* across the world today (Marszal et al., 2011; Sartori, Napolitano, & Voss, 2012). It is possible to distinguish five main areas in which definitions may differ from each other. These five areas, which also should be clearly defined and described in connection with a definition of *Net ZEB* are:

- Building system boundary
- Weighting system
- Net ZEB balance
- Energy match characteristics
- Verification and measurements

Defining the building system boundary includes the physical boundary, the balance boundary and boundary conditions. The physical boundary should be defined in order to be able to quantify energy flows delivered and exported to the building and also to define "on-site". The most common boundary conditions chosen to define "on-site" are the building foot print or site. However, some methodologies acknowledge the option of off-site renewable supply, for example off-site windmills (Marszal et al., 2011). The term "balance boundary" refers to defining which energy uses are included in the Net ZEB balance, i.e. whether or not all the energy use related to building operation, *OE*, is included in the balance. When energy uses included in *OE* are defined, the terminology defined in EN 15603:2008 (Swedish Standards Institute, 2008) should be used to enable transparency. Boundary conditions include defining the external climate and the use of the building, e.g. indoor temperature, air change rate, etc.

Defining the weighting system should include choice of metrics and weighting factors. Today there are projects claiming Net ZEB balance based on delivered energy, primary energy, CO_2 credits and costs, etc. where primary energy is the most favoured metric (Marszal et al., 2010b). Weighting factors differ widely between countries and concepts (Sartori, Napolitano, & Voss, 2012).

In Sweden it is customary to value the energy performance of buildings based on delivered energy, which also may be denoted as un-weighted or final energy, due to the fact that legal requirements are set in that metric (Boverket, 2011). However, the Swedish Net ZEB definition applies weighting factors when the balance is calculated and refers to the metric as "weighted energy".

As the building system boundary and weighting system are defined, the weighted supply and demand may be calculated. The requirement and core principle is shown in Equation 2.1.

$$Net\,ZEB : |WS| - |WD| \geq 0$$ Equation 2.1

Where

WS Weighted supply
WD Weighted demand

Often an annual balance is applied for *Net ZEBs* but there are also cases where the balance is calculated monthly, seasonally or over several decades. When the time span is longer than one year, usually the approach is to grasp the balance over the entire life cycle, including the embodied energy.

The Net ZEB balance, Equation 2.1, may be calculated differently with respect to time span and whether import/export balance or load/generation balance is preferred. A load/generation balance is fairly easy to calculate since there is no need to take into account the interplay between the two. However, measuring the performance of a *Net ZEB* is likely to be done by measuring the energy delivered to the building and the energy exported from the building. Hence, the import/export balance is measured. Note that load/generation and import/export balance would appear at different points in the zero balance graph, Figure 2.2. This is due to the fact that the import/export balance considers the energy consumed within the building plus distribution and storage losses.

There may also be design requirements included in a Net ZEB definition. These design requirements may be related to energy efficiency (e.g. specific U-values of envelope components or performance of HVAC systems). But they can also be design requirements relating to other qualities (e.g. thermal comfort or acoustic requirements).

In addition to the Net ZEB balance, the interaction with the grid and the ability to cover the energy demand by on-site generation may be quantified by using load match and grid interaction indicators, *LMGI* indicators. The *load match*, Equation 2.2, refers to how the local energy supply compares with the energy demand. When energy is fed into the grid, the *load match* is 100%. The *load match index*, Equation 2.3, is the lowest load match over the year.

$$f_{load,i,(t)} = \min\left(1, \frac{g_i(t) + dc_i(t) - c_i(t)}{l_i(t)}\right)$$ Equation 2.2

$$f_{load,i,year,(t)} = \min\left(f_{load,i,(t)}\right)$$ Equation 2.3

Where

$g_i(t)$	Generation of energy carrier, i, at the time step t
$dc_i(t)$	Discharge energy of carrier, i, from storage at the time step t
$c_i(t)$	Charging energy of carrier, i, to storage at the time step t
$l_i(t)$	Load of energy carrier, i, at the time step t

The grid interaction, defined in Equation 2.4, refers to the energy exchange between the building and the grid and is based on the ratio between the net metering (e.g. exported/delivered energy) compared to the maximum exported/delivered energy. When a building exports energy, the result of the calculated grid interaction is positive. The average stress on the grid, *grid interaction index*, is described in Equation 2.5 using the standard deviation of the grid interaction over the period of a year. For both load match index and grid interaction index, calculations should be carried out for each energy carrier, i, at a time interval, t, relevant for the analysis.

$$f_{grid,i,(t)} = \frac{e_i(t) - d_i(t)}{\max\left|e_i(t) - d_i(t)\right|} \qquad \text{Equation 2.4}$$

$$f_{grid,i,year,(t)} = \mathrm{STD}\left(f_{grid,i,(t)}\right) \qquad \text{Equation 2.5}$$

Where

$e_i(t)$	Exported energy of carrier, i, at the time step t
$d_i(t)$	Delivered energy of carrier, i, from the grid at the time step t

Several other indicators exist to analyze load matching and the interaction between the building and the grid (Berggren, Widén, Karlsson, & Wall, 2012; Salom et al., 2011; Voss et al., 2010).

Last but not least, a Net ZEB definition should also state how to verify and measure the performance of the Net ZEB.

2.1.4 Energy efficiency indicators for the building envelope

Transmission heat transfer throughout the building envelope was studied in Papers I, III and VIII, focusing on the state of knowledge among engineers and architects, possible effects of misunderstandings and the distribution of transmission heat transfer throughout the building envelope.

A common indicator, used to quantify the energy efficiency of a building element, is to calculate the thermal transmittance, U, which includes the thermal resistance of the different wall layers and the surface resistance, including conduction, radiation and convection. The EPBD states that the methodology for calculating the energy performance of buildings should take into account European standards. Hence, the thermal transmittance may be calculated according to EN ISO 6946 (Swedish Standards Institute, 2007a) that specifies how to calculate thermal resistance and thermal transmittance.

The amount of insulation and the thermal conductivity of the insulation are key parameters that influence the thermal transmittance of a building element. The thermal conductivity of an insulation material may vary with temperature, humidity, age and due to natural convection. Conversion of thermal conductivity from one set of conditions to another set of conditions may be done according to EN ISO 10456 (Swedish Standards Institute, 2007b) as shown in Equation 2.6 which considers temperature, humidity and aging. At present, there is no commonly accepted calculation procedure to consider the effect of natural convection on thermal conductivity. The modified Raleigh number, Ra_m, may be used to describe the risk of natural convection as shown in Equation 2.10. If Ra_m is less than the critical values defined in Table 2.2, there is no need for correction of thermal conductivity due to natural convection.

$$\lambda_2 = \lambda_1 F_T F_m F_a \qquad \text{Equation 2.6}$$

Where

λ_1 Thermal conductivity for the first set of conditions (W/mK)
F_T Conversion factor for temperature
F_m Conversion factor for moisture
F_a Conversion factor for aging

Age conversion is not defined in EN ISO 10456. Aged values or ageing factors are usually provided by manufacturers or defined in product standards. Conversion factor for temperature is described in Equation 2.7. Equation 2.8 and Equation 2.9 describe the conversion factor for moisture where one of the equations shall be used, based on the input data available.

$$F_T = e^{f_T (T_2 - T_1)} \qquad \text{Equation 2.7}$$

Where

f_T Temperature conversion coefficient
T_1 Temperature for first set of conditions (K)

T_2 Temperature for second set of conditions (K)

$$F_m = e^{f_u(u_2-u_1)} \qquad \text{Equation 2.8}$$

Where

f_u Moisture conversion coefficient, mass by mass
u_1 Moisture content for first set of conditions, mass by mass
u_2 Moisture content for second set of conditions, mass by mass

$$F_m = e^{f_\psi(\psi_2-\psi_1)} \qquad \text{Equation 2.9}$$

Where

f_ψ Moisture conversion coefficient, volume by volume
ψ_1 Moisture content for first set of conditions, volume by volume
ψ_2 Moisture content for second set of conditions, volume by volume

$$Ra_m = 3\times10^6 \frac{dk\Delta T}{\lambda} \qquad \text{Equation 2.10}$$

Where

d Thickness of insulation (m)
k Permeability of insulation (m^2)
ΔT Temperature difference across the insulation (K)

Table 2.2 Critical modified Rayleigh number

Direction of heat flow	Ra_m
Horizontal	2.5
Upwards, open surface	15
Upwards, wind protected open surface	30

Within a Norwegian research project, ROBUST (Norges forskningsråd, 2008), detailed measurements of wall constructions have shown that natural convection may develop at lower Ra_m than 2.5 (Uvsløkk, Skogstad, & Grynning, 2010). A similar study was conducted based on field measurements and numerical validation (Nore & Clementz, 2011). The study showed that a convection barrier improved the performance of a wall construction, insulated with 400 mm of insulation. However, the improvement was low and the authors conclude that there is not a clear need for a convection barrier in order to provide energy savings or a more moisture safe construction. Good craftsmanship and wise detailing are more important.

To evaluate an entire building envelope, the transmission heat transfer coefficient may be calculated according to EN ISO 13789 (Swedish Standards Institute, 2007c) which is shown in Equation 2.11.

$$H_T = H_D + H_g + H_U + H_A \qquad \text{Equation 2.11}$$

Where

H_D	Direct heat transfer coefficient, defined in Equation 2.12 (W/K)
H_g	Steady-state ground heat transfer coefficient, calculated according to EN ISO 13370 (W/K)
H_U	Transmission heat transfer coefficient through unconditioned places (W/K)
H_A	Transmission heat transfer coefficient to adjacent buildings (W/K)

$$H_D = \sum_i A_i U_i + \sum_k l_k \Psi_k + \sum_j \chi_j \qquad \text{Equation 2.12}$$

Where

A_i	Area of element, *i* (m^2)
U_i	Thermal transmittance of element, *i* (W/m^2K)
l_k	Length of linear thermal bridge, *k* (m)
Ψ_k	Linear thermal transmittance of thermal bridge, *k* (W/mK)
χ_j	Point thermal transmittance through point thermal bridge, *j* (W/K)

To calculate the transmission heat transfer coefficient for the entire building envelope of a building, the building envelope needs to be clearly defined and divided into different elements and applicable standards may be applied for different parts as shown in Figure 2.4.

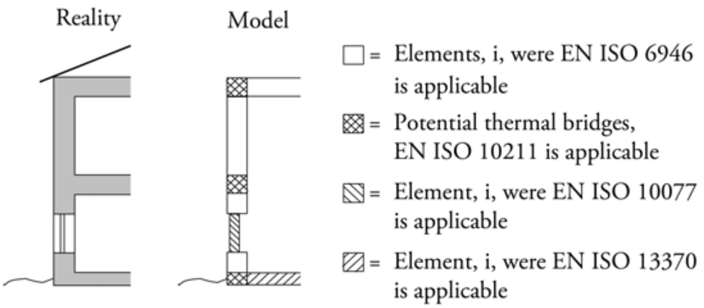


Figure 2.4 Breakdown of building into different elements and thermal bridges

EN ISO 13789 allows quantification of elements and thermal bridges measured according to one of the three methods; internal, overall internal or external dimensions. The differences between the measuring concepts are shown in Figure 2.5.

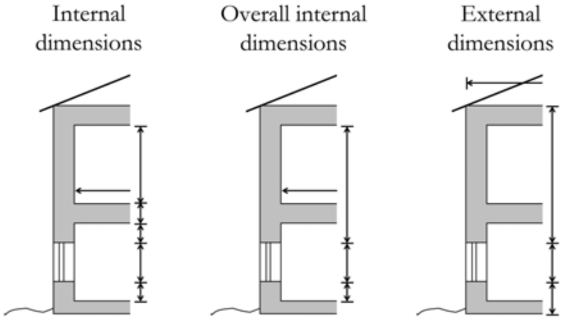


Figure 2.5 Different types of dimensions according to EN ISO 13789

Thermal bridges are calculated according to EN ISO 10211 (Swedish Standards Institute, 2007d) as shown in Equation 2.13 and Equation 2.14.

$$\Psi = L_{2D} - \sum_{j=1}^{N_j} U_j \cdot l_j \qquad \text{Equation 2.13}$$

Where

L_{2D} Thermal coupling coefficient obtained from a 2-D calculation (W/mK)
U_j Thermal transmittance of 1-D component, j (W/m^{2}K)
l_j Length over which U_j applies (m)

$$\chi = L_{3D} - \sum_{i=1}^{N_i} U_i \cdot A_i - \sum_{j=1}^{Nj} \Psi_j \cdot l_j \qquad \text{Equation 2.14}$$

Where

L_{3D} Thermal coupling coefficient obtained from a 3-D calculation (W/K)
U_i Thermal transmittance of 1-D component, i (W/m^{2}K)
A_i Area over which U_i applies (m^2)
Ψ_j Linear thermal transmittance calculated according to Equation 2.13 (W/mK)
l_j Length over which Ψ_j applies (m)

The sum of transmission losses through building elements, the term $\Sigma A_i U_i$, will vary depending on the chosen measuring method. Consequently, the thermal bridges, Ψ-values and χ-values, will vary. However, the transmission heat transfer coefficient will be the same provided that the same measuring method is consistently used in all calculations.

It is important to consistently apply one measuring method throughout an analysis of transmission heat transfer coefficient for an entire building envelope and to understand the effects of the chosen measuring method. A recent survey in Sweden shows that the state of knowledge within this field, among engineers and architects, is low. Results from the survey are presented in Papers I & VIII and a Swedish trade journal (Berggren & Wall, 2012c).

The survey indicated that engineers and architects do not understand that a thermal bridge, by definition, also occurs when there is a difference between internal and external area. Furthermore, different measuring methods are applied, simplified calculations are used to account for thermal bridges and it is not possible to conclude that a specific measuring method prevails. The relative impact of thermal bridges increases when the thermal resistance of the building envelope increases. Simplified methods, such as accounting for thermal bridges by increasing U-values for building envelopes by a fixed percentage, are not suitable to use (Berggren & Wall, 2011b, 2012c, 2013). There is a high risk of misunderstanding and the consequences may be underestimation of energy demand for space heating and peak load for heating amounting to almost 40 % and 30 % respectively (Berggren & Wall, 2011b). This may lead to poor indoor climate and to economical consequences for the builder, the client and/or the consultants. To clarify which measuring method, used to calculate the thermal transmittance of thermal bridges, the subscripts presented in Table 2.3 may be used.

Table 2.3 Subscripts to clarify used method for measuring

Subscript	Definition
i	Internal
oi	Overall internal
e	External

If a building element generates renewable energy, e.g. converting solar energy into useful energy for the building, the performance can be evaluated by calculating the energy balance as shown in Equation 2.15. This can be applied to windows and building elements with integrated solar energy systems.

$$E = |l_i| - |g_i| \qquad \text{Equation 2.15}$$

Where

l_i Load for energy carrier, i, caused by building element or elements
g_i Generation of energy carrier, i, due to building element or elements

The energy balance may be calculated by using advanced simulation software or simplified methods such as the “Karlsson method” (Roos & Karlsson, 1998). However, if simplified methods are used, one needs to be careful in interpreting the result since simplified methods may not consider whether or not the generated energy is useful (Karlsson, Karlsson, & Roos, 2001).

To quantify the capacity of storing thermal energy within a building element or a complete building system/building envelope, the volumetric heat capacity may be calculated. The volumetric heat capacity is determined by multiplying the density with the specific heat capacity.

2.1.5 Embodied energy

Embodied energy, *EE*, and life cycle energy, *LCE*, analysis of buildings were studied in Paper VI.

Today, no international definition of *EE* exists. To ensure transparency the international guidelines may be used; ISO 14040 and ISO 14044 (Swedish Standards Institute, 2006a, 2006b), when *LCE* analysis or other Life Cycle Analysis, *LCA,* is reported.

The total *LCE* of a building may be divided into (Ramesh, Prakash, & Shukla, 2010):

- Initial embodied energy, EE_i
  where EE_i includes the initial embodied energy within a material or a product plus the energy used for transportation and assembly on site
- Recurring embodied energy, EE_r
  where EE_r includes energy within materials and processes due to renovation and refurbishments
- Operating energy, *OE*
  where *OE* is the energy consumed to maintain the desired indoor environment in a building which therefore may include all types of energy used defined by EN 15603:2008.
- Demolition energy, *DE*
  where *DE* is the energy required to demolish the building and to transport materials to land fill or recycling. The quantities of energy recycled should be subtracted from *DE*

Using the definitions above the *LCE* may be defined as in Equation 2.16 and Equation 2.17.

$$LCE = EE_i + EE_r + OE + DE \qquad \text{Equation 2.16}$$

$$LCE = \underbrace{\sum m_i M_i + E_C + E_{TC}}_{EE_i} + \underbrace{\sum m_i M_i \left(\frac{L_b}{L_{mi}} - 1 \right)}_{EE_r} + \underbrace{E_{OA} L_b}_{OE}$$

$$+ \underbrace{E_D + E_{TW} + \left(\left(E_R \right)(-1) \right)}_{DE} \qquad \text{Equation 2.17}$$

Where

m_i	Quantity of building material, i
M_i	Energy content of the material, i
E_C	Energy consumed on site for construction of building
E_{TC}	Energy used for transportation on and off site during construction phase
L_b	Life span of building
L_{mi}	Life span of material, i
E_{OA}	Annual operating energy
E_D	Energy used for demolition of building
E_{TW}	Energy used for transportation of waste materials off site after demolition
E_R	Energy that may be recycled or extracted, e.g. burning

Note that specific units are not defined in Equation 2.15. Hence, different units are used. E.g. kWh, MJ etc. for energy and kg, m^3 etc. for quantities.

As for the definition of a Net ZEB it is possible to distinguish areas where a calculation of *EE* and therefore also *LCE* differs (Berggren, Hall, & Wall, 2013):

- Metric of balance
- Life span
- Boundary conditions
- Age of data
- Data source

Primary energy is a common metric used when *EE* and *LCE* are presented, but also final energy is used. A comprehensive study made on 57 different case studies (Sartori & Hestnes, 2007) shows that 79% of the case studies use primary energy to evaluate the *EE*. The assumed life span varies greatly, 30-100 years, where the most favoured life span is 50 years (Berggren, Hall, & Wall, 2013).

Boundary conditions may be divided into two categories; material included and limitations in downstream/upstream process included. Considering material included in the analysis; it is always complex to carry out a complete LCE analysis of a building, including all materials. To enable analysis of a specific measure one may analyze only the effects of that specific measure by calculating the Energy Payback Time, *EPT*, Energy Payback Ratio, *EPR*, or the Net Energy Ratio, *NER*, of that specific measure. The bases for the analyses are shown in Equation 2.18, Equation 2.19 and Equation 2.20.

$$EPT = \frac{\Delta EE_T}{\Delta OE} \qquad \text{Equation 2.18}$$

Where

ΔEE_T Total difference in embodied energy due to the specific measure
ΔOE Annual difference in operating energy due to the specific measure

$$EPR = \frac{\Delta OE_T}{\Delta EE_T} \qquad \text{Equation 2.19}$$

Where

ΔOE_T Total difference in operating energy due to the specific measure

$$NER = \frac{\Delta OE}{\Delta EE} \qquad \text{Equation 2.20}$$

Where

ΔEE Annual difference in embodied energy due to the specific measure

It shall be noted that these simplified analyses; *EPT*, *EPR* and *NER*, do not usually include *DE*. However, the effect of energy used for the demolition may be expected to be small. One extensive Swedish study showed that the relative share of *LCE* due to *DE* was <1% (Adalberth, 1997). Other studies have shown that the *DE* was negative, i.e. the energy extracted from the materials through recycling and combustion exceeded the energy needed for disassembly (Adalberth, 1999; Blengini & Di Carlo, 2010; Dodoo, Gustavsson, & Sathre, 2011).

Age of data may have a significant impact as old data may be derived from an obsolete technology of manufacturing that is not as energy efficient as the new technology and thus, they differ in their values. As an example, the energy used to produce photovoltaics has significantly decreased and the energy payback time is today considered to be under five years compared to when old technology was used in the 1970s and the energy payback time was 20 years (Alsema & WildScholten, 2007).

The source of data may have a significant impact on the result of *LCE* analysis and due to the unclear definition of *LCE*; researchers use different approaches to collect data. Some refer to existing databases or to previous studies and others develop own embodied energy coefficients (Dixit, Fernández-Solís, Lavy, & Culp, 2010).

Today, a number of tools and databases are available that can be used to compile and analyze embodied energy for building envelopes. As age of data may have a significant impact on the result, there is a constant need for maintenance and updating of these databases and tools. Therefore, the use of tools and databases is usually associated with a cost. There is no commonly used commercial or public database of embodied energy for different materials in Sweden. Three examples of commercial tools that can be found in Canada, U.S.A. and Germany are EcoCalculator (Athena Institute, 2013), BEES (NIST Building and Fire Research Laboratory, 2011) and Legep (WEKA MEDIA GmbH & Co. KG, 2012).An example of a public database is the Inventory of Carbon & Energy (Hammond, Jones, Lowrie, & Tse, 2008). Data used in studies in Sweden has mainly been based on data from previous studies. Examples may be found in (Adalberth, 1997, 1999; Dodoo, Gustavsson, & Sathre, 2011; Gustavsson, Joelsson, & Sathre, 2010; Thormark, 2002).

Comparing old studies of embodied energy in buildings from 1970-1990 and studies of embodied energy in buildings built today, there is a small decrease in embodied energy, *EE*. However, *EE* as the relative share of the total life cycle energy, *LCE*, is increasing. The threshold of when *EE* > 50% of *LCE* is at *OE* of 33 kWh/m^{2}a and 45 kWh/m^{2}a for residential and non-residential buildings respectively (Berggren, Hall, & Wall, 2013). In studies that clearly reported *EE* broken down in different parts of the building; building envelope, load bearing constructions, installations, etc, the main contributor to the *EE* is materials used within the building envelope and load bearing constructions (Adalberth, 1999; Berggren, Hall, & Wall, 2013; Blengini & Di Carlo, 2010).

2.1.6 Generating energy

In order to reach the Net ZEB balance, it is almost a must to generate energy on site. It may be avoidable, if off-site production of energy based on renewable energy sources is allowed within the specific definition. Within an overview of 50 exemples of *Net ZEBs* from different countries and climate regions, presented in 2010 (Musall et al., 2010), none of the leading *Net ZEBs* exist without Photovoltaic, *PV*, panels. The second most common technology for on-site generation of energy is solar thermal collectors, *ST* collectors, followed by heat pumps and combined heat- and power plants, *CHP*. A general conclusion may be that a *Net ZEB* in a mid-European climate needs to install *PV*; 40 Wp/m^2A_C and ST collectors; 0.7 m^2, *ST*/m^2A_C (Berggren, Hall, & Wall, 2013; Musall et al., 2010;

Musall & Voss, 2012). Both PV panels and ST collectors may have an effect on the performance of the building envelope if they are mounted onto the building envelope or if they are an integral part of the building envelope. Heat pumps or *CHPs* do not have such a direct effect and are therefore not described here.

PV cells turn photon energy into electric energy. One single cell can produce about 0.5 V when irradiated. Normally these cells are put together in series in PV modules and into a PV panel. The PV panel can be connected to a battery or the grid. The PV produces DC voltage. Therefore, a converter, transforming DC voltage into AC voltage, will be needed if the *PV* is to be connected to a grid. In addition to the converter, electric cabling and monitoring system and possibly mounting equipment is needed. There are many different types of PV cells that vary in efficiency, appearance and price. The efficiency may vary between 8% and 17% (Davidsson, 2010). When PV cells are put together in series it is of the utmost importance that no part of the PV panel is shaded as this affects the total performance of the module. A comprehensive study of 200 PV systems in Germany showed that 41% of the systems suffered from poor performance due to partial shading (Laukamp, Schoen, & Ruoss, 2002).

ST collectors utilize the heat of solar radiation and transfer it to the building system for hot water or space heating system. Most ST collectors use the same basic idea; an absorber transfers the heat from the solar energy to a circulating liquid heat medium. The most common types are flat plate collectors, vacuum tube collectors and concentrating collectors. When energy is generated on-site; one should always try to first use the energy on-site instead of exporting the energy to the grid. This priority is based partly on reducing the stress on the grid (applies to both heat and electricity), partly on the fact that less energy may be utilized when heat is exchanged with a local district heating network, because of distribution losses and because a district heating network usually operates at a rather high temperature (Berggren, Widén, Karlsson, & Wall, 2012).

2.1.7 Boundary conditions affecting the energy performance of buildings

Regarding the outdoor climate, the outdoor temperature is a key parameter affecting the energy demand for space heating for buildings. Simple tools for calculating the energy performance, such as TMF-Energy 2.2, only consider outdoor temperature (Ruud & Rosenkilde, 2011). Slightly more advanced tools, such as ENORM (EQUA, 2004) also consider solar radiation. Advanced tools used today consider at least the outdoor temperature, solar radiation, outdoor relative humidity, *RH*, and wind.

As building envelopes are designed with lower and lower transmission heat transfer losses, the relative effect of other factors may increase. A recent study (Bagge, 2011) shows that a large proportion of the energy use for space heating in buildings is related to outdoor temperature. However, the effect of wind and solar radiation is also considerable. Therefore, when simulations are conducted to predict the energy demand and energy performance of buildings, taking into consideration future climate scenarios, these parameters should be taken into account. It shall be noted that the study (Bagge, 2011) was conducted for residential buildings situated at a windy location and designed with relatively large window areas. Hence, airtight, energy efficient buildings with moderate window areas will likely be less affected.

As buildings are designed and constructed to be more energy efficient, the interior heat gains from occupants and electricity use within the building from plug loads and lighting become more important (Johansson & Bagge, 2011). Furthermore, if a Net ZEB balance, Equation 2.1, is calculated on import/export balance, the assumed user behaviour, the electricity use, consumption of hot water etc., must be defined at a minimum hourly resolution in order to calculate the exchange to the grid. Other key parameters are the desired indoor temperature (Bagge, 2011), ventilation rate (Janson, 2010).

2.2 Moisture performance

Calculation methodologies and moisture performance of buildings were studied in Papers IV and V.

When the term energy performance, *EP*, is used in relation to buildings, it generally refers to energy use related to conditioned area, as once defined in the EPBD (European Parliament, 2003). However, the definition of moisture performance is not that clear. Use of the term moisture performance may refer to the hygrothermal characteristics of a specific construction or material. It may also refer to the risk of performance failure due to exceeding a critical hygrothermal condition. There is no international or European standard for assessing and presenting moisture performance.

2.2.1 Legal requirements regarding moisture safety for residential buildings in Denmark, Finland, Norway and Sweden

In the Danish building regulations there are no quantified levels regarding specific hygrothermal conditions which shall not be exceeded. The requirements are functional requirements, stating that buildings should not suffer from performance failure due to hygrothermal conditions (Erhvers- og Byggestyrelsen, 2010). The regulations refer to guidelines (Møller et al., 2010; Møller & Vestergaard, 2009). The guidelines provide critical conditions of rust and mould growth. Critical conditions of mould growth for different materials are given as static levels, Table 2.4, and graphically in isopleths, Figure 2.6. An equation for critical conditions for mould growth, RH_{crit}, in relative humidity is also presented, Equation 2.21.

Table 2.4 Critical relative humidity, *RH*, for mould growth on surface of construction materials. Long term exposure at 20°C. From (Møller & Vestergaard, 2009), based on (Johansson et al., 2005)

Material	Critical RH [%]
Wood and wood based materials	75-80
Cardboard on gypsum boards	80-85
Mineral wool	90-95
Expanded polystyrene (EPS)	90-95
Concrete	90-95
Soiled materials	75

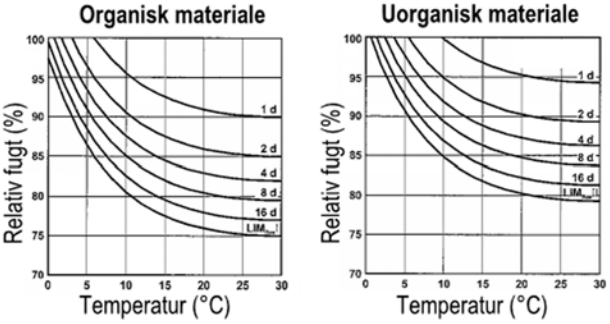


Figure 2.6 *Relationship between mould growth, temperature, relative humidity and duration (days=d) at constant temperature and relative humidity. Picture from (Møller et al., 2010), based on (Sedlbauer, 2001). Translation; Temperatur = Temperature, Relativ fugt = Relative humidity, Organsik = Organic, Uorganisk = Inorganic & Materiale = Material*

$$RH_{crit} = 0.02\theta^2 - 1.18\theta + 95.2 \qquad \text{Equation 2.21}$$

Where

θ Temperature (°C)

In Finland, the building regulations require that buildings shall be designed and built so as not to pose risks due to moisture accumulation. Water vapour, water and snow from interior or exterior climate shall not be able to penetrate building constructions (Ympäristöministeriö, 1998). The regulations and guidelines do not specify any quantified critical conditions.

In Norway, the building regulations require that water or water vapour, from interior or exterior climate, shall not penetrate the building and cause mould growth or other hygienic problems. The guidelines for the building regulations (Direktoratet for byggkvalitet, 2011) do not state any quantified critical hygrothermal conditions.

The Swedish building regulations state that buildings shall be designed so that neither building structures nor spaces in buildings can be damaged by moisture (Boverket, 2011). A maximum permitted moisture level shall be used for materials and surfaces where mould and bacteria may grow. The maximum critical moisture level shall be based on the specific critical moisture level, taking into account unreliability in assessments. If the critical moisture level for a material is not well-researched and documented, a RH_{crit} of 75% shall be used.

2.2.2 Common indicators of moisture safety assessment in environmental indicator systems

Within the environmental indicator systems, mentioned in Section 2.1.2, the only one that states quantified indicators to prevent performance failure due to moisture is the Swedish criteria for passive houses, see Table 2.5. Three of the remaining indicator systems demand that a person, responsible for monitoring moisture safety, is appointed. Furthermore, they require inspections/controls and documentation throughout the building process. Two require only inspections/controls and documentation throughout the building process. Two have no requirements regarding moisture safety.

Table 2.5 Maximum moisture content in wood (Sveriges Centrum för Nollenergihus, 2012)

	Maximum moisture content [kg/kg]
Delivered on-site and during construction before interior and exterior cladding	<0.20
During building operation and when interior and exterior cladding is mounted	<0.16

2.2.3 Critical hygrothermal conditions and assessment of risk of performance failure

Within the building construction industry, robustness and durability of building elements are often based on experience. The experiences are often expressed qualitatively, and not specified in quantitative terms.

Performance failure due to high levels of moisture content or relative humidity is often associated with risk of mould growth. However, other risks may also occur. Examples of changes due to the influence of unfavourable moisture conditions may be corrosion, swelling, shrinking etc.

The critical response time for growth of mould fungi on pine and spruce sapwood was presented in the late 1990s based on relative humidity and temperature. The critical response time is presented in Equation 2.22, based on constant climate conditions (Viitanen, 1997).

$$t_{mp} = \exp(-0.67 \ln T - 13.15 \ln RH + 62.60)$$
$$t_{ms} = \exp(-0.74 \ln T - 15.53 \ln RH + 73.79)$$
$$t_{vp} = \exp(-0.71 \ln T - 12.32 \ln RH + 59.50)$$
$$t_{vs} = \exp(-0.76 \ln T - 13.20 \ln RH + 63.80)$$

Equation 2.22

Where

t_{mp}	Response time for initial stages of mould growth on pine sapwood (weeks)
t_{ms}	Response time for initial stages of mould growth on spruce sapwood (weeks)
t_{vp}	Response time for visual appearance of mould growth on pine sapwood (weeks)
t_{vs}	Response time for visual appearance of mould growth on spruce sapwood (weeks)
T	Temperature (°C)
RH	Relative humidity (%)

Similar exponential curves were presented for three different groups of materials in 2001 (Sedlbauer, 2001). These curves are referred to in the Danish guidelines and presented in Figure 2.6.

In 2005, a literature review (Johansson et al., 2005) was conducted at SP Technical Research Institute of Sweden. The purpose of the literature review was to compile the state of knowledge regarding criteria for mould growth related to *RH*. The study resulted in proposals for RH_{crit} for six different groups of materials, also referred to in the Danish guidelines, presented in Table 2.4.

A later study (Nilsson, 2006) compiled RH_{crit} and critical moisture content from an extensive literature review. This study was not limited only to mould growth. A summary of the literature review is presented in Table 2.6. The study also remarks that a condition where RH_{crit} or critical moisture content is exceeded need not trigger any consequences if the duration is short.

Table 2.6 Critical moisture levels for change (Nilsson, 2006)

Change	Material	RH_{crit} [%]	Critical moisture content [kg/kg]
Swelling when *RH* increases	Wood- and cement based materials	60-80	
Shrinkage when *RH* decreases	Wood- and cement based materials	30	
Mechanical properties	Wooden materials		0.25-0.30
	Linoleum mat	90	
Transport of dissolved substances	Cement based materials	70	
Cementitious reactions	Cement based materials	85	
Carbonation	Limestone based materials	50-85	
Alkali protein reactions	Cement based materials, high pH	80	
Alkali ballast reactions	Cement based materials, high pH	85	
Corrosion	Metals	50	
	Reinforcement steel in carbonated concrete	85	
	Reinforcement steel in chloride concrete	<60	
Mould growth (visible in microscope)	Wooden surfaces	80	
Mould growth	Wooden surfaces	85	
Mould growth + release of toxic	-	85	
Rot	Wooden materials		25-30
Self-emissions	Chipboards	65	
Secondary (chemical) emissions	Chipboards	80	
	PVC mat	90	

A recently published thesis (Johansson, 2012) presents critical moisture levels for the onset of mould growth for ten materials, commonly used in buildings. The critical moisture levels are based on constant climate and are presented for two different temperatures as set out in Table 2.7.

Table 2.7 Critical moisture levels for onset of mould growth (P. Johansson, 2012)

Material	Temperature	
	22°C	10°C
Pine sapwood	$75<RH_{crit,\ 12\mathrm{w}}\leq 79$	$85<RH_{crit,\ 12\mathrm{w}}\leq 90$
Plywood	$75<RH_{crit,\ 12\mathrm{w}}\leq 79$	$75<RH_{crit,\ 12\mathrm{w}}\leq 85$
Chipboard	$79<RH_{crit,\ 12\mathrm{w}}\leq 85$	$90<RH_{crit,\ 12\mathrm{w}}\leq 93$
Thin hardboard	$85<RH_{crit,\ 12\mathrm{w}}\leq 89$	$93<RH_{crit,\ 12\mathrm{w}}\leq 95$
Wet-room gypsum plaster board	$89<RH_{crit,\ 12\mathrm{w}}\leq 95$	$95<RH_{crit,\ 12\mathrm{w}}$
Exterior gypsum plaster board	$89<RH_{crit,\ 12\mathrm{w}}\leq 95$	$95<RH_{crit,\ 12\mathrm{w}}$
Asphalt paper	$89<RH_{crit,\ 12\mathrm{w}}\leq 95$	$95<RH_{crit,\ 12\mathrm{w}}$
Cement based board	$95<RH_{crit,\ 12\mathrm{w}}$	$95<RH_{crit,\ 12\mathrm{w}}$
Glass fibre	$95<RH_{crit,\ 12\mathrm{w}}$	$95<RH_{crit,\ 12\mathrm{w}}$
Expanded polystyrene	$95<RH_{crit,\ 12\mathrm{w}}$	$95<RH_{crit,\ 12\mathrm{w}}$

As shown in this section, the risk of performance failure due to moisture conditions is strongly related to hygrothermal conditions and the duration of the specific condition. Hygrothermal conditions are fluctuating. Therefore, different models may be applied to calculate the risk of performance failure due to moisture.

Two models have been developed in Sweden to assess the potential for mould growth on wood. The first model, referred to as the “Dose-model” in this thesis, was developed at Lund University (Isaksson, Thelandersson, Ekstrand-Tobin, & Johansson, 2010). This model is based on the critical time, t_{ms}, of mould growth on spruce sapwood, under different climatic conditions based on the critical response time, presented in Equation 2.20 (Viitanen 1997). The model uses daily averages of temperature and relative humidity as input data.

The second model, referred to as the m-model in this thesis, was developed at Skanska Sverige AB. The purpose was to enable assessment and comparison of different design solutions from a mould risk perspective (Tengberg & Togerö, 2010; Togerö, Tengberg, & Bengtsson, 2011). The m-model is similar to the ”Dose-Model” since this model also is based on calculating the critical time for when mould is in theory initiated. However, the m-model enables evaluations based on shorter time steps, 1-3 hours, and uses six different duration curves for which mould in theory is initiated, compared to the Dose-model, which only uses one duration curve.

In addition to the software WUFI Pro (Fraunhof-Institut fur Bauphysik, 2013), a plug-in to assess the risk of mould growth is available; WUFI Bio. The model used for analysis is different from models described above. Within the model a hypothetical mould spore is given characteristics of sorption of water and diffusion of water vapour. If the water content within the mould spore exceeds critical levels, mould growth is initiated. Critical levels for mould growth may be chosen for different substrate classes. The pace of mould growth is related to the level of water content. The model is thoroughly described in (Sedlbauer, 2001, 2003). The result of the evaluations is presented on a seven-point scale, defined by (Viitanen & Ritschkoff, 1991).

A simplified method for risk assessment was introduced at the 3rd Nordic Passive House Conference 2010 (Hagentoft, 2010).The model uses a non-dimensional temperature factor, ξ, to calculate the relative humidity at any point in a construction as shown in Equation 2.23.

$$RH = \frac{v_e + \Delta v}{v_s\left(T_e + \xi \cdot \left(T_i - T_e\right)\right)} \qquad \text{Equation 2.23}$$

Where

RH	Relative humidity (%)
v_e	Outdoor humidity by volume (g/m^3)
Δv	Local moisture supply (g/m^3)
v_s	Saturation vapour content for the temperature T (g/m^3)
T_e	External/outdoor temperature (°C)
T_i	Interior/indoor temperature (°C)
ξ	Relative temperature factor (-)

Below is an example of a simple risk analysis conducted using the "Hagentoft-method". The example is based on an insulated wood frame wall with a steel column. The relative temperature distribution is shown in Figure 2.7.

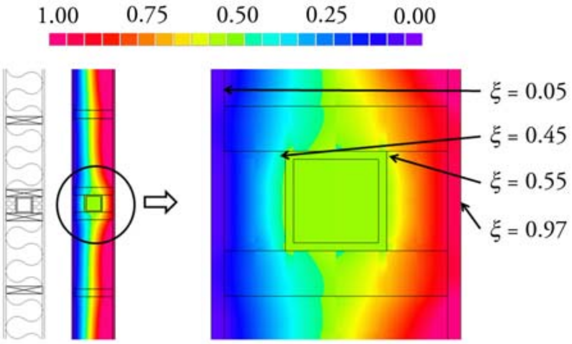


Figure 2.7 *Insulated wood frame wall with steel column, 100x100x8. Analysis of relative temperature, using HEAT 2 (Blocon Sweden, 2008)*

By applying an exterior climate based on a reference climate for Lund, 55.7°N, 13.2°E, assuming the indoor temperature to be 21°C, it is possible to examine the risk of performance failure; the results are presented in Figures 2.8 and 2.9. The monthly average temperatures and relative humidity are presented together with the critical relative humidity for corrosion (Nilsson, 2006) and onset of mould growth on insulation (Johansson, 2012), onset of mould growth on cardboard on gypsum plasterboard (Johansson et al., 2005) and onset of mould growth on spruce at different temperatures for t_{ms}=30 days.

Corrosion on the steel column is likely at moderate moisture supply, which may be handled by rust proofing. In addition to the corrosion, there is a risk of onset of mould growth on the exterior side of the wall during the heating season at high moisture supply (twice as high as the initial assumption). Furthermore, onset of mould growth may occur on the interior gypsum plaster board.

The assumed moisture supply in the later analysis is very high but may occur if ventilation of a building is not fully functioning in combination with incorrect mounting of the vapour barrier.

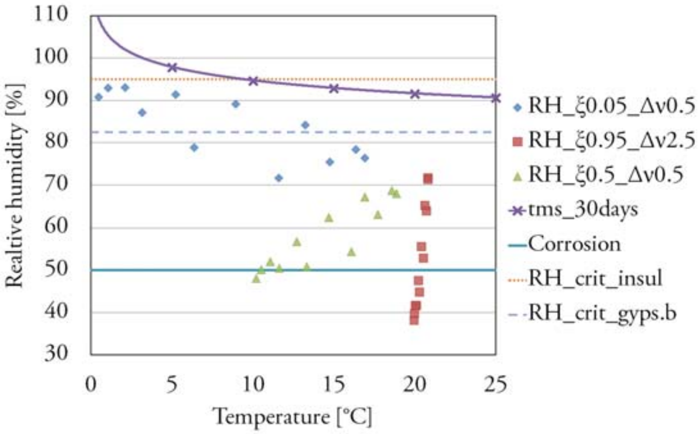


Figure 2.8 *Risk assessments with different relative temperature factor ξ, based on HEAT analysis. Moderate moisture supply, Δv*

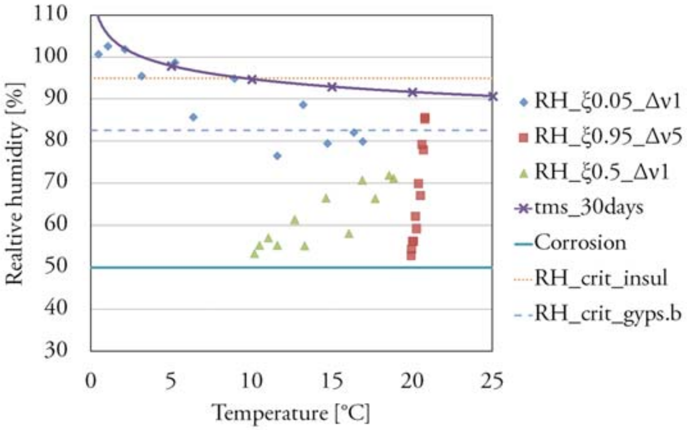


Figure 2.9 *Risk assessments with different relative temperature factor ξ, based on HEAT analysis. High moisture supply,* Δv.

Within this study, all models are investigated and tested based on simulations considering future climate scenarios (Berggren & Wall, 2012a, 2012b). The investigations indicate that the ongoing climate change will most likely increase the risk of mould growth.

2.2.4 Boundary conditions – affecting buildings' moisture performance

To determine moisture distribution within a building element, based on a 1-D steady-state calculation, often the resistance to moisture flow, *Z*, is calculated for each section of a specific material followed by calculating the vapour content at a specific position as shown in Equation 2.24 (Sandin, 1997).

$$v_n = v_1 \frac{Z_n}{\sum Z_n} \cdot (v_1 - v_2) \qquad \text{Equation 2.24}$$

Where

v_n Humidity at position *n* (g/m^3)
v_1, v_2 Humidity at each side of building element (g/m^3)
Z_n Resistance to moisture flow ($\cdot 10^3$ s/m)

This serves as a basis for calculations of relative humidity and dew point. Examples may be found in DIN 4108-3 (Deutsches Institut für Normung, 2012) and EN 13788 (Swedish Standards Institute, 2001). These methods assume moisture transfer to be pure water vapour diffusion. Boundary conditions that need to be defined to use these methods, and to calculate the relative humidity, are temperature and humidity at each side of the building element.

To assess moisture transfer in building elements by numerical simulation, more parameters are needed. A complete set of parameters describing the external climate should contain temperature, humidity, solar radiation, sky temperature, wind, precipitation and total atmospheric pressure at each time step, according to EN 15026 (Swedish Standards Institute, 2007e). The interior climate should be defined by temperature and humidity. Atmospheric pressure has a minor effect. Therefore, mean value over a calculation period can be sufficient (Schmidt, 2009). The interior humidity and temperature may be defined by using standards such as EN 13788, EN 15026 or ASHRAE 160 (ASHRAE, 2009). More detailed data could be used from (Bagge, 2011).

2.3 Future boundary conditions

2.3 1 Outdoor climate

Future boundary conditions, considering outdoor climate were studied in Paper V.

As described in Sections 2.1.7 and 2.2.4, there are a number of parameters, boundary conditions, needed in order to evaluate a building's or building elements' energy and moisture performance. Buildings have a long life span. It is therefore necessary to consider climate change when conducting these evaluations. There are different methods to generate future climate data for simulations and estimations of building performance in respect to climate change. Several studies and proposals have been published. These may be divided into four groups, from simple to complex; extrapolating statistical method, the imposed offset method, stochastic weather model and climate models (Guan, 2009). The extrapolating statistical method, also called degree-day method, has the benefits of being simple and fast. However it has been proven to be fairly coarse and often not suitable as input data for simulations (Guan, 2009). Two examples of stochastic weather models may be found in (Adelard, Boyer, Garde, & Gatina, 2000; Paassen & Luo, 2002). The remaining two groups are based on climate models. The imposed offset method bases the climate data on a typical year, meteorological – TMY, or reference – TRY. Known parameters that are expected to be affected by climate change are adjusted by offsetting the parameters based on the results from the climate models. This method has been used in many studies and has the benefit that it can be used even if changes of all parameters are unknown. However, if output data from a regional climate model, RCM, is available it may be used. It has the benefit of generating physically consistent data and there is no need to apply modification methods (Nik, Kalagasidis, & Kjellström, 2012).

Climate models are used to simulate and produce climate scenario data. These climate scenarios are not weather forecasts. They are scenarios based on emissions scenarios from IPCC Special Report on Emissions Scenarios, SRES (IPCC, 2000). The climate scenarios answer the question; if the atmosphere is changing in a certain way, how will the climate change?

There are 40 different scenarios, grouped into four families. There are no disaster scenarios. The families differ whether there will be focus on the economy or the environment. Furthermore, they differ regarding whether there will be an increased globalization or regionalization. The differences are schematically described in Figure 2.10.

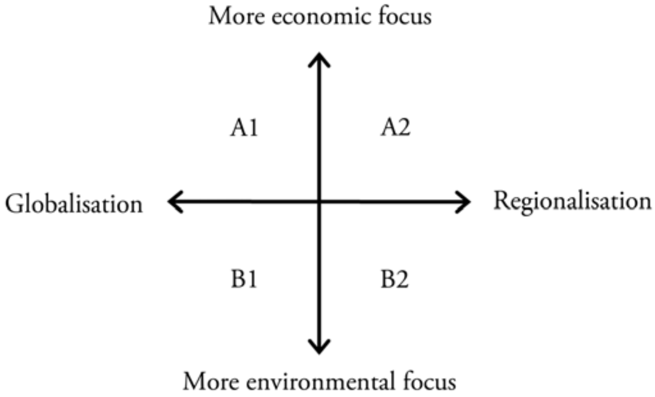


Figure 2.10 Schematic presentation of the scenario families; A1, A2, B1 and B2

The A1-family is divided into three groups; A1FI, A1B and A1T. In Figure 2.11, the annual emissions of CO_2 are presented for all scenarios divided into the four families.

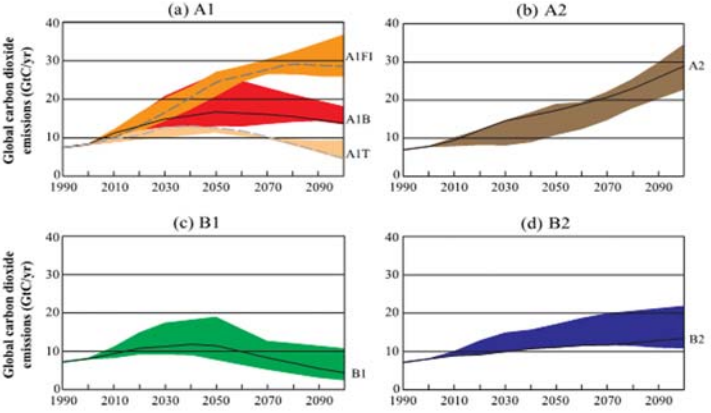


Figure 2.11 *Total global annual CO_2 emissions for the 40 SRES (IPCC, 2000)*

Global climate models, GCMs, are representations of physical processes within and between the atmosphere, land surface, oceans and sea ice. GCMs require a lot of computing power. Therefore, the grid in global climate models usually has a sparse resolution and gives little detail on the regional and local scale. Regional climate models, RCMs, can be used to study specific areas in more detail, e.g. Europe. A small area makes it possible to have a denser grid, and consequently more detailed results. The boundary conditions for a RCM are coupled to a GCM. The Rossby Centre at the Swedish Meteorological and Hydrological Institute, SMHI, uses three-dimensional regional climate models that mathematically describe the climate system with a fairly high resolution.

Climate data for scenarios A1B, A2, B1 and B2 is available today from SMHI. The RCM used is RCA3 (Samuelsson et al., 2011). The RCA3 model covers Europe with a horizontal resolution of 50x50 kilometres. The boundary conditions are from the global climate model ECHAM5 (Roeckner et al., 2003) or ECHAM4 (Roeckner et al., 1996). The simulations cover the period 1961-2100. A large amount of data distributed over various parameters is stored in the RCA simulations. Based on the previous sections stating important boundary conditions, Table 2.9 summarises data, deemed to be useful for this study.

Table 2.8 Climate data from SMHI

Input data needed for simulations	Available parameter from SMHI			
	Abbreviation/Code	Name	Unit	Time step (h)
Atmospheric pressure	1 105 0	Surface Pressure	Pa	0.5
Temperature	11 105 0	Surface temperature	K	6
	11 100 850	Temperature	K	6
Wind	33 100 850	U-Component of wind	m/s	6
	34 100 850	V-component of wind	m/s	6
Relative humidity	52 100 850	Relative humidity	-	6
Precipitation	61 105 0	Total precipitation	mm/s	0.5
	65 105 0	Snowfall	mm/s	0.5
Sky temperature	71 105 0	Total cloud cover	-	3
	71 109 22	Total cloud cover	-	6
	71 109 23	Total cloud cover	-	6
	71 109 24	Total cloud cover	-	6
Solar radiation	116 105 0	Downw. Short-wave radiation surf	W/m²	0.5

As can be seen in Table 2.8, the data is presented in different time steps and often in time steps > 1h. The parameters gathered from SMHI need to be downscaled to daily averages; used to offset typical meteorological years at different locations in Sweden. This enables use of the imposed offset method to generate climate data in this study. Initial tests have been made using data from SMHI using the imposed offset method based on monthly averages presented in Papers IV and V, showing an increased risk of performance failure due to hygrothermal conditions as an effect of climate change.

2.3.2 Indoor climate

To enable simulations to predict energy performance and hygrothermal conditions, input data is needed regarding desired indoor climate and internal loads in terms of heat gains, moisture supply, etc. In non-residential buildings there may be complex installations to control and regulate the indoor climate, including relative humidity, maximum and minimum temperature, level of CO$_2$ and other pollutants. In residential buildings, in general, the only controlled and regulated parameter is minimum temperature. Furthermore, a specific air change rate is desired. Generally, the air change rate in Swedish dwellings may be expected to be ≥0.35 l/s, m$^2 A_C$ (Boverket, 2011) which corresponds to 0.5 h^{-1} in a room with the height of 2.5 m. The air change rate 0.5 h^{-1}is frequently used in national standards in Europe (Dimitroulopoulou, 2012).

The Swedish building regulations recommend that energy calculations in the design stage may use 22°C as the average indoor temperature for dwellings (Boverket, 2011). In addition there is a general recommendation in Sweden to use a heating set point of 21°C for simulations of both multi dwelling buildings and one- and two dwelling buildings (Levin, 2009). However, 22°C is a more correct heating set point for multi dwelling buildings in reference to expected operating conditions for buildings and 21°C may be used for one- and two-dwelling buildings (Bagge, 2011; Boman, Jonsson, & Skogber, 1993; Levin, Blomsterberg, Wahlström, & Gräslund, 2007).

Since residential buildings in general are expected not to have cooling systems, the indoor temperature will most likely exceed the heating set point especially outside of the heating season. This is usually calculated in simulation programs used to calculate energy performance of buildings. However, simulation programs used to analyse hygrothermal conditions for building elements may use a simplified method to define the indoor temperature outside the heating season. ISO 13788 (Swedish Standards Institute, 2001) suggests that the indoor temperature may be set as a fixed value throughout the year. EN 15026 (Swedish Standards Institute, 2007e) and AHRAE 160 (ASHRAE, 2009) suggest that the indoor temperature exceeds the heating set point outside of heating season, following Equation 2.25 and 2.26 respectively. Measurements conducted in Swedish dwellings show higher indoor temperatures compared with EN 15026 and ASHRAE 160 (Bagge, Johansson, & Lindstrii, 2011). The study proposes to use indoor temperatures presented in Equation 2.27 as a base line to define Swedish hygrothermal conditions.

$$\begin{aligned} T_i &= 20 && \text{for}\, T_{\bar{e},daily} \leq 10 \\ T_i &= 15 + 0.5T_{\bar{e},daily} && \text{for}\, 10 < T_{\bar{e},daily} < 20 \\ T_i &= 25 && \text{for}\, T_{\bar{e},daily} \geq 20 \end{aligned}$$

Equation 2.25

$$\begin{aligned} T_i &= 21.1 && \text{for}\, T_{\bar{e},24h} \leq 18.3 \\ T_i &= T_{\bar{e},24h} + 2.8 && \text{for}\, T_{\bar{e},24h} > 18.3 \end{aligned}$$

Equation 2.26

$$\begin{aligned} T_i &= 22.3 && \mathit{for}\, T_e \leq 7.5 \\ T_i &= 20.68 + 0.216T_e && \mathit{for}\, 7.5 < T_e < 20 \\ T_i &= 25 && \mathit{for}\, Te \geq 20 \end{aligned}$$

Equation 2.27

Where

T_e External/outdoor temperature (°C)

$T_{\bar{e},daily}$ Daily average of external/outdoor temperature (°C)

$T_{\bar{e},24h}$ 24-hour running average external/outdoor temperature (°C)

There is also a need to consider the relative humidity and/or the moisture supply in the indoor environment. This may be calculated, using a simulation software or by applying standardized values. For dwellings and offices with a normal occupancy the indoor relative humidity may be assumed to conform to Equation 2.28 according to EN15026 or Equation 2.29 according to ASHRAE 160. ISO 13788 states that a moisture supply to indoor air for dwellings, with low occupancy, should conform to Equation 2.30. It shall be noted that none of the standards, EN 15026, ASHRAE 160 or ISO 13788, defines "normal". Hence, these boundary conditions should be seen as simplified approaches that may be used in the absence of well defined (controlled) or simulated internal air conditions.

The measurements mentioned above (Bagge, Johansson, & Lindstrii, 2011), show that the moisture supply and relative humidity are lower compared to EN 15026 and ISO 13788. They suggest using Equation 2.31 for relative humidity and Equation 2.32 for moisture supply.

$$\begin{aligned} RH_i &= 30 && \text{for}\, T_{\bar{e},daily} \le -10 \\ RH_i &= 40 + T_{\bar{e},daily} && \text{for} -10 < T_{\bar{e},daily} < 20 \\ RH_i &= 60 && \text{for}\, T_{\bar{e},daily} \ge 20 \end{aligned}$$

Equation 2.28

$$\begin{aligned} RH_i &= 40 && \text{for}\, T_{\bar{e},daily} \le -10 \\ RH_i &= 50 + T_{\bar{e},daily} && \text{for} -10 < T_{\bar{e},daily} < 20 \\ RH_i &= 70 && \text{for}\, T_{\bar{e},daily} \ge 20 \end{aligned}$$

Equation 2.29

$$\begin{aligned} \Delta v &= 4 && \text{for}\, T_{\bar{e},monthly} \le 0 \\ \Delta v &= 4 - 0.2T_{\bar{e},monthly} && \text{for}\, 0 < T_{\bar{e},monthly} < 20 \\ \Delta v &= 0 && \text{for}\, T_{\bar{e},monthly} \ge 20 \end{aligned}$$

Equation 2.30

$$
\begin{aligned}
RH_i &= 30 && \text{for}\, T_{\bar{e},daily} \leq -2.5 \\
RH_i &= 32.857 + 1.1429 T_{\bar{e},daily} && \text{for} -2.5 < T_{\bar{e},daily} < 15 \\
RH_i &= 50 && \text{for}\, T_{\bar{e},daily} \geq 15
\end{aligned}
$$

Equation 2.31

$$
\begin{aligned}
\Delta v &= 2 && \text{for}\, T_{\bar{e},daily} \leq 0 \\
\Delta v &= 2 - 0.1 T_{\bar{e},daily} && \text{for}\, 0 < T_{\bar{e},daily} < 17 \\
\Delta v &= 0.3 && \text{for}\, T_{\bar{e},daily} \geq 17
\end{aligned}
$$

Equation 2.32

Where

$T_{\bar{e}}$, *monthly* Monthly average of external/outdoor temperature (°C)

Based on previous studies (Ellegård, 2002; Forum för Energieffektiva Byggnader, 2008; Levin, Blomsterberg, Wahlström, & Gräslund, 2007; Zimmermann, 2009) SVEBY recommends heat gains from persons to be set to 80 W/person (Levin, 2009). Based on their recommended occupancy levels for different sizes of dwellings and assuming sizes of dwellings, the average heat gains from occupancies varies between 1.1-2.2 W/m^2, see Table 2.9.

Table 2.9 Internal heat gains from occupants based on SVEBY (Levin, 2009)

	Number of rooms in dwelling (excluding kitchen and bathrooms)						
	1*	1	2	3	4	5	≥6
Recommended occupancy level (person/dwelling)	1.42	1.42	1.63	2.18	2.79	3.51	3.51
Heat gains (W/person)	80	80	80	80	80	80	80
Average presence time (%)	58	58	58	58	58	58	58
Assumed size of dwelling (m^2)	30	40	50	70	90	120	150
Calculated heat gains (W/m^2)	2.2	1.7	1.5	1.5	1.4	1.4	1.1

*No kitchen, only kitchenette

In a recent study, hourly occupancy levels were calculated based on measurements of CO_2 in 342 dwellings in multi family houses. The heat gains from occupants vary between 1.2-2.5 W/m^2 based on yearly average heat gains over a day (Bagge, 2011). The highest heat gains occur in the last three hours before midnight.

Detailed data on electricity use for household purposes in 400 dwellings are presented in (Zimmermann, 2009). Hourly data for electricity use is also presented in (Bagge, 2011). The first study presents the electricity use as W/dwelling, while the latter presents the findings in W/m^2. The average annual heat gains from electricity use are presented together in Figure 2.12. In Figure 2.13 the variation of electricity loads in dwellings over a day in relation to daily top load is presented. The highest electricity use varies slightly between the different categories and studies. In general the highest use occurs in the afternoon between 5 P.M. and 10 P.M.

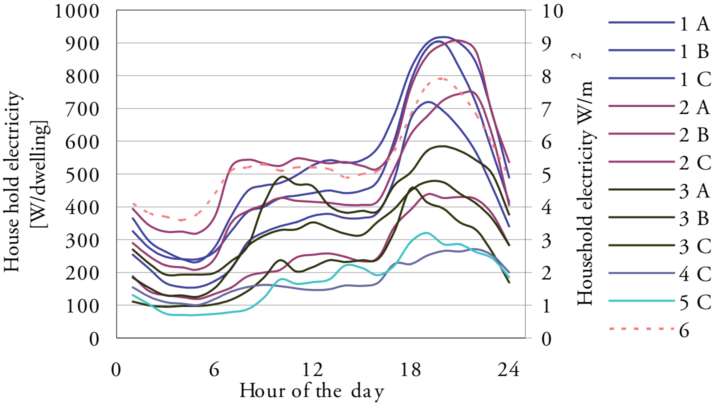


Figure 2.12 *Variation of electricity loads in dwellings over a day. 1-5 (Zimmermann, 2009) are read on left y-axis. 1=families, 2=couples (26-64 years), 3=couples (>64 years), 4=Singles (26-64 years), 5=singles (>64 years). A=detached house, electric heating, B=detached, other heating, C=apartment in multi dwelling building. 6 (Bagge, 2011) is read on right y-axis.*

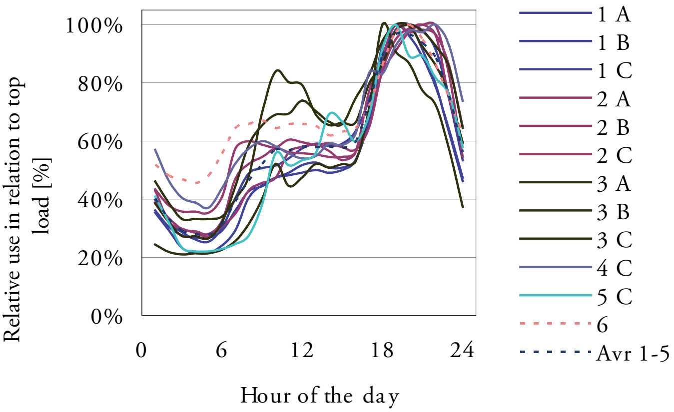


Figure 2.13 *Variation of electricity loads in dwellings over a day in relation to daily top load. 1-5 (Zimmermann, 2009) 1=families, 2=couples (26-64 years), 3=couples (>64 years), 4=Singles (26-64 years), 5=singles (>64 years). A=detached house, electric heating, B=detached, other heating, C=apartment in multi dwelling building. 6 (Bagge, 2011).*

Use of household electricity in Sweden has increased from 9 to 19 TWh between 1970 and 2009. Most of the increase occurred in the 1970s - and 1980s and can be explained by an increased number of households and an increase in household equipments. Since 2001, the use of household electricity has remained at a relatively steady level (Energimyndigheten, 2011). The use of electricity is affected by two opposing trends. The number of appliances and features on different devices in households are increasing. At the same time, the trend is towards more energy-efficient appliances. In view of this, it is difficult to predict future electricity use in dwellings. However, the relative electricity use may follow the profile presented in Figure 2.13.

The daily variation in hot water loads presented in (Bernado, 2010; Widén et al., 2009) is plotted in Figure 2.14.

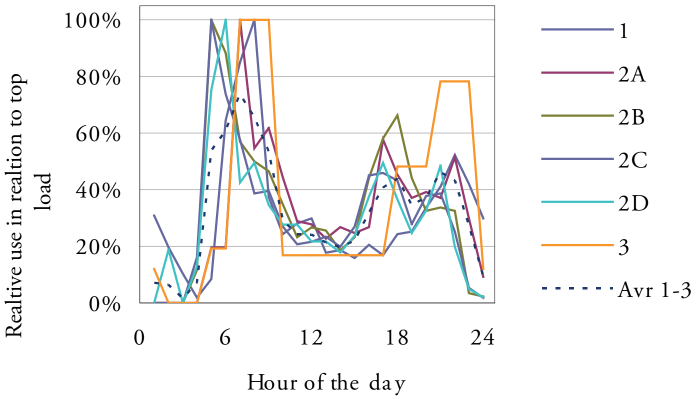


Figure 2.14 *Variation in hot water loads in dwellings over a day. 1-2 (Widén et al., 2009), 3 (Bernado, 2010) 1=detached house, 2=apartment in multi dwelling building, measurement from four different occasions, 3=model used for detached house.*

Daily variation is important to take into account to investigate the grid interaction and load match if energy is generated from solar or wind on site. However, applying daily variation has a small impact on the annual energy performance compared with seasonal variation (Johansson & Bagge, 2011). Seasonal variations in electricity use are presented as curves in (Zimmermann, 2009) and (Johansson & Bagge, 2011). The variations are presented graphically in Figure 2.15 and as Equations 2.33-2.38.

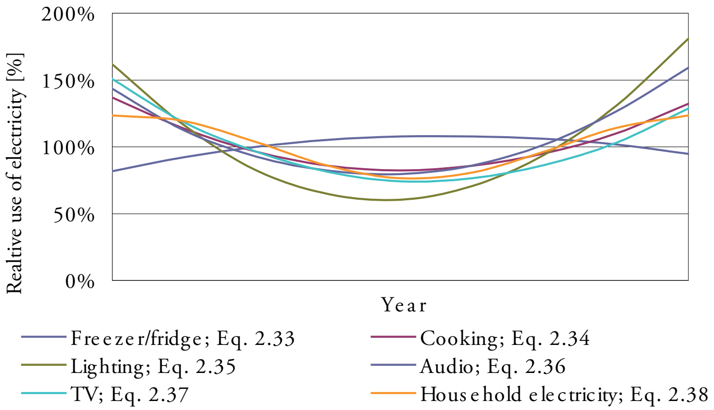


Figure 2.15 *Seasonal variation in electricity loads. Household electricity is from (Johansson & Bagge, 2011), all others (Zimmermann, 2009).*

$$\beta_{electricity} = -0.78(t)^2 - 0.98(t) + 0.82 \qquad \text{Equation 2.33}$$

$$\beta_{electricity} = 2.08(t)^2 - 2.12(t) + 1.37 \qquad \text{Equation 2.34}$$

$$\beta_{electricity} = 4.44(t)^2 - 4.24(t) + 1.62 \qquad \text{Equation 2.35}$$

$$\beta_{electricity} = 2.87(t)^2 - 2.70(t) + 1.43 \qquad \text{Equation 2.36}$$

$$\beta_{electricity} = 2.60(t)^2 - 2.81(t) + 1.50 \qquad \text{Equation 2.37}$$

$$\beta_{electricity} = 1 + 0.238 \cdot \sin(2\pi \cdot t + 1.42)$$

$$\text{where} \quad t = \frac{h}{8760} \qquad \text{Equation 2.38}$$

Seasonal variation is also described by using monthly offset factors in (Sveriges Centrum för Nollenergihus, 2012) as presented in Table 2.10.

Table 2.10 Monthly variation in domestic hot water and household electricity (Sveriges Centrum för Nollenergihus, 2012)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Household electricity	1.25	1.22	1.15	1.00	0.88	0.78	0.73	0.75	0.83	1.00	1.16	1.25
Domestic hot water	1.13	1.16	1.13	1.09	0.89	0.84	0.71	0.74	0.94	1.09	1.13	1.15

2.4 Quality assessment – Multi criteria decisions

As shown in Sections 2.1 and 2.2, there are many different indicators that may be used to quantify a building or a building element in respect to energy and moisture performance. The indicators are expressed in different units, thus creating a multi criteria decision problem. Multi criteria decision analysis, MCDA, multiple attribute decision making, MADM, or multi criteria decision making, MCDM, is often referred to as a quantitative approach assisting decision making where there are multiple, conflicting goals, expressed in dissimilar units. Such analysis may be solved by applying a mathematical method, henceforth in this thesis referred to as multi criteria decision analysis, MCDA. However, it is important to highlight that there is no such thing as a "right answer" or an optimum within the concept of MCDA. It should rather be perceived as a working method which enables stakeholders to manage subjectivity and to integrate objective/quantitative and value judgement. The benefit of MCDA is that it may increase the transparency of a decision making, enabling stakeholders to better understand the decision from their own and from others' perspectives (Belton & Stewart, 2002).

Multi criteria decision analysis may be conducted in many other different ways. One of the earliest known descriptions of a method for decision making, applied on multi criteria problems, refers to Benjamin Franklin who recommended that one should write down all the pros and cons on separate sides of a piece of paper and estimate their "weights". Then strike out all the arguments on each side that are of relative equal importance. If one argument is equal to two arguments on the other side; strike all three out etc. Using this procedure, Franklin could find the balance in his decision (MacCrimmon, 1973).

2.4.1 Different methods of MCDA in environmental indicator systems

Many environmental indicator systems use a form of MCDA. Using an environmental indicator system often enables the stakeholder to find technical solutions that provide “the highest ranking”. This may seem contradictory to the statement above that there is no “right answer”. This is because many subjective decisions are already done within the environmental indicators systems, e.g. which indicators/values are important, how should we evaluate them relative to each other etc.

Within the environmental indicator systems, mentioned in Section 2.1.2, different methods are used to present the performance of the analysed building.

A common method, used in LEED, Bream and Svanen, is to have a predetermined point value of a number of indicators which may be fulfilled partly or fully. The rating of the building is determined by summarizing the “earned points”.

In “Miljöbyggnad” the overall rating is based on weighting of many indicators. The indicators are aggregated into different sub criteria and the sub criteria are aggregated into three different main criteria. The basic framework is schematically presented in Figure 2.16.

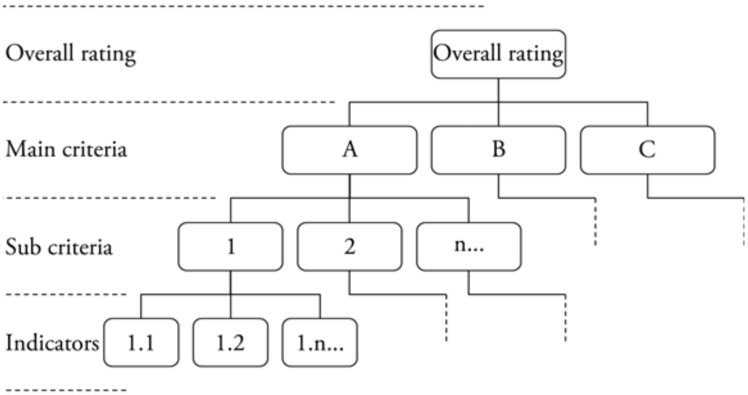


Figure 2.16 Schematic presentation of value tree in “Miljöbyggnad”

Each indicator is rated in a four graded scale; gold, silver, bronze and classified. Classified is equal to fulfilment of the basic requirements within

"Miljöbyggnad". Gold is the highest rating. The weighting of the indicators is done by a specific aggregation system. Aggregating the indicators to a rating of a sub criterion; the lowest indicator sets the rating of the sub criterion. Aggregating the sub criteria into a rating of a main criterion; the same procedure is used. However, if ≥50% of the other sub criteria have a higher rating, the rating is raised one step. The overall rating is set by the lowest rating within the three main criteria. This procedure is graphically described in Figure 2.17.

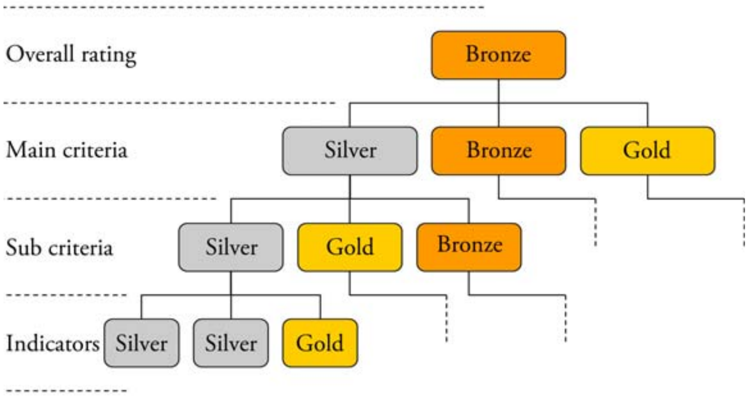


Figure 2.17 Aggregating of rating in "Miljöbyggnad"

Another way of presenting a multi MCDA is used in "Miljöbyggprogram SYD". This system uses six indicators to express the performance of the building. Each indicator is graded A-C, where C is the lowest and A is the highest grade. The grades are translated into numerical values as follows; A=3, B=2 and C=1. The overall rating of the building is presented by summarising the numerical values and presenting the rating of the different indicators in a radar chart as presented in Figure 2.18. A similar way, often used, presents the result in a spider chart, Figure 2.19.

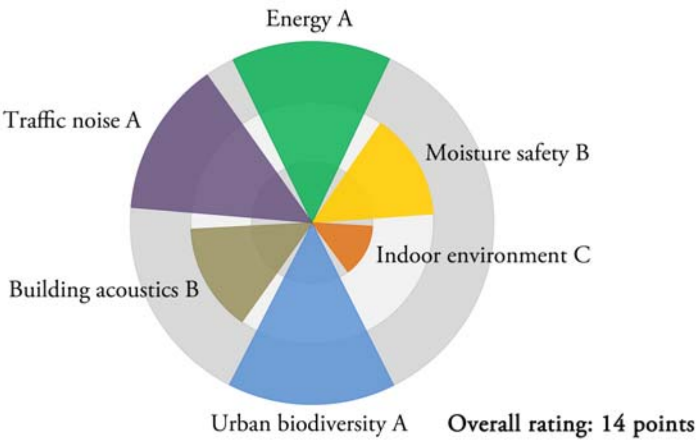


Figure 2.18 *Radar diagram, based on example from "Miljöbyggprogram SYD" (Malmö stad & Lunds kommun, 2012).*

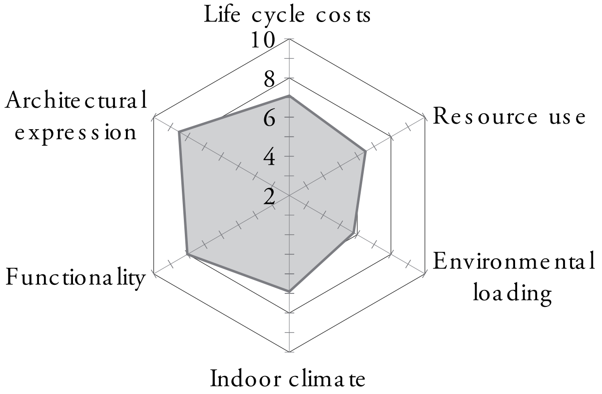


Figure 2.19 *Star diagram, based on example from (Andresen & Hestnes, 2007)*

2.4.2 MCDA – Theoretical framework for modelling

To create a model which may represent stakeholders' preferences and value judgements, two main components need to be addressed: preferences and aggregation. Preferences refer to how criteria are valued. E.g. what indicator or indicators is/are used and how different levels of performance for each indicator are relatively valued. Aggregation is the model which allows all the criteria to be weighted into an overall rating or value. This is commonly illustrated as a "value tree", presented in Figure 2.16. A rule of thumb may be that the indicators are stated in a way that enables almost an unambiguous assessment of the indicator. If this is not possible, the sub criterion should be broken down into a new set of more detailed sub criteria before broken down into indicators.

To enable evaluation of different indicators in a simple way, one must assume that preferences and values of indicators are transitive. E.g. if $a>b$ and $b>c$, then $a>c$ (Belton & Stewart, 2002). Indicators may be defined in a way that increasing or decreasing values are preferred. In this section, it is always assumed that decreasing values are preferred.

When a set of criteria are broken down into indicators, the relative value of the indicator needs to be defined. E.g. if alternative *a* takes three days to carry out and alternative *b* takes six days, how are these two alternatives valued relative to each other? Below three basic methods are described.

The first method involves that a stakeholder (or several stakeholders) defines a best and worst accepted indicator. Based on these, it is assumed that indicators outperforming the best value have the same value as best value. Indicators below worst accepted value are equal to zero. Values in between are assumed to have a linear distribution, this is presented graphically as method 1 in Figure 2.20.

The second method involves defining one or several values in-between the accepted best and worst values. A possible effect of the two methods is graphically described in Figure 2.20.

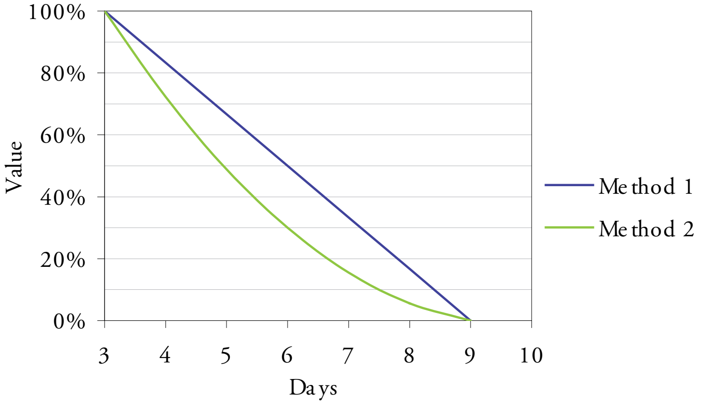


Figure 2.20 Value as a function of days to complete an action

Using the first method, the value decreases from 100% to 50% when the duration is increased from three days to six days, increasing the time by three days. Using the second method, the duration only needs to be increased by roughly two days, from three to five days to decrease the value to 50%. Examining the example, the second method in this case, enables the stakeholder to value time saving relatively low when the duration is long. Consequently, time savings when the duration is short are valued higher.

The third method, based on the standard ASTM E1765-11 (ASTM International, 2011), uses a matrix to enable pairwise comparisons. An example of on evaluation matrix based on the example described above is presented in Table 2.11.

Table 2.11 Matrix for pairwise comparison

		Indicator (Days)		
		3	6	9
		Verbal expression		
		Excellent	Good	Acceptable
Indicator (Days)	3	1	Desirability of 3 over 6	Desirability of 3 over 9
	6	Desirability of 6 over 3	1	Desirability of 6 over 9
	9	Desirability of 9 over 3	Desirability of 9 over 6	1

The desirability of 3 days over 6 days is defined by 3/6=0.5, the desirability of 3 days over 9 days is defined by 3/9=0.33 and so on. When the indicator in the left column is less desirable compared to the second indicator, the value is inverted. Finally, if decreasing values are preferred, all desirability indicators are inverted. The result of the calculations of desirability is presented in Table 2.12. Based on the matrix, three days are 3.00 times more desirable compared to nine days, six days is 1.50 times more desirable compared to nine days, etc.

Using this method, no indicator will get a relative value of zero.

Table 2.12 Matrix for pair wise comparison

		Verbal expression		
		Excellent	Good	Acceptable
		Indicator (Days)		
		3	6	9
Indicator (Days)	3	1	2.00	3.00
	6	0.50	1	1.50
	9	0.33	0.67	1

In this case, the indicator is already given in a digitalised value; days. However, the method may be used when verbal expressions or different classes, such as A, B, C, D etc are compared. In principle, there is no limitation to the size of the matrix system described above. However, ten levels may be considered as a practical maximum (Öberg, 2005).

When all indicators are transferred into values, the overall value is aggregated. In its simplest form this is done by summarising all values. However, a weighting factor may be preferred. Using weighting factors, the overall value is then calculated according to Equation 2.39.

$$V(a) = \sum_{1}^{i} w_i v_i(a) \qquad \text{Equation 2.39}$$

Where

$V(a)$	The total value of the investigated alternative *a*
w_i	Weighting factor for criterion *i*, for all alternatives
v_i	Relative value for criterion *i*, for alternative *a*

The weighting factors may be set subjectively or by using one of the two methods described below.

The first method, sometimes referred to as the “swing weight method” (Belton & Stewart, 2002), is based on firstly indentifying the indicator considered to be of greatest importance. Secondly, all other indicators are valued relatively to the most important indicator. To translate the evaluation into a numerical value, a predefined scale may be used as below;

- Equally important/The most important = 5
- Less important = 3
- Not so important = 1

Often, scales with more “steps” are used. Five-step-scales or seven-steps-scales are often used, both when evaluating the relative value of indicators and the relative importance of indicators. Examples may be found in (Andresen & Hestnes, 2007; Schade, Olofsson, & Schreyer, 2011; Öberg, 2005).

When all indicators are relatively valued in relation to the most important indicator, the weighting factor is defined by dividing the set value by the sum of all indicators’ value. One example, using the swing weight method, is presented below. To define the weighting between indicators i_1, i_2, i_3, i_4 and i_5, the indicator i_2 is identified as the most important indicator. The result of the relative evaluation and weighting factors is presented in Table 2.13.

Table 2.13 Relative evaluation of importance of indicators

Indicator	Numerical value	Normalised weighting factor
i_1	1	0.06
i_2	5	0.29
i_3	3	0.18
i_4	3	0.18
i_5	5	0.29

Using a scale with more steps may differentiate the values more than the result in Table 2.13. However, one disadvantage, using the swing weight method, is that indicators that are valued equally in relation to the most important indicator (in this case i_3 and $_{i4}$) are not relatively valued towards each other.

By using an evaluation matrix, as presented in Figure 2.12, it is possible to evaluate all indicators relative to each other. In Table 2.14, the same example given with the same evaluation as above is presented. However, in this case, i_5 is valued less important than i_2 and i_4 less important than i_3. The normalized eigenvector of the matrix calculates the priority. Calculating the normalized eigenvector may be a rather complex operation, especially for large matrices. Today, usually different computer programs are used for the operation. As can be seen in Table 2.14, there is now a relative difference between the indicators i_5 - i_2 and i_4 - i_3.

Table 2.14 Relative evaluation of importance of indicators

	i_1	i_2	i_3	i_4	i_5	Priority (eigenvector)
i_1	1	1/5	1/3	1/3	1/5	0.05
i_2	5/1	1	3/1	3/1	3/1	0.42
i_3	3/1	1/3	1	3/1	1/3	0.16
i_4	3/1	1/3	1/3	1	1/3	0.10
i_5	5/1	1/3	3/1	3/1	1	0.27

This method is often referred to as the Analytic Hierarchy Process, AHP, presented in (Saaty, 1980). Within the EU-project; InPro (InPro, 2010), the method was adopted and tested in a case study (Schade, Olofsson, & Schreyer, 2011). The authors conclude that the method increases the transparency of decision making and the client may become more involved in the decision making in the design process.

2.5 Summary

When the energy performance of buildings is described, it is usually the annual energy use divided by conditioned area that is referred to. However, differences exist between different countries regarding what energy use to include, how to verify the energy performance etc. A Net Zero Energy Building is a building where renewable energy generation covers the energy use. Also within this expression differences exist between different definitions.

Energy efficiency of building elements and the building envelope is commonly expressed as thermal transmittance, U, or total transmission heat transfer, H_T, including thermal bridges. The calculation methodologies for transmission heat transfer throughout the building envelope are well defined but allow for different measuring methods to be used in order to quantify the building elements. This increases the risk of misunderstandings and misinterpretations. This has been investigated through a questionnaire, verifying that Swedish engineers and architects use different measuring methods and are not fully aware of the concept of thermal bridges.

Embodied energy of buildings has slightly decreased, shown by comparison of studies conducted before 1990 and today. However, as buildings today are more energy efficient and are using less energy in the operational phase, the relative share of embodied energy in the total life cycle energy use increases. The main contributor to the embodied energy is the building envelope and loadbearing constructions.

The term moisture performance may refer to characteristics of a material/construction or risk of performance failure due to hygrothermal conditions. However, there is no international or European standard defining "moisture performance". Legal requirements regarding moisture safety differ between the different investigated countries. Critical hygrothermal conditions are different for different materials. Furthermore the duration of specific conditions is also important. Hence there is a need to apply evaluation models that can consider fluctuating conditions.

There is a need to consider the effect of climate change as the initial studies show an increased risk of performance failure due to climate change. There are data available today for different climate scenarios from the Swedish Meteorological and Hydrological Institute, SMHI, which may be used. The reviewed publications, treating indoor climate, show different models to define the indoor climate. Different models are also available for assumptions regarding energy use for household purposes and use of hot water. Studies have shown that consideration of the seasonal variation of electricity use for household purposes and the use of hot water has a greater impact on the energy performance of buildings than the daily variation. However, daily variation is important to consider if grid interaction and load match are to be investigated.

Multi Criteria Decision Analysis, MCDA, is a method for support decision making when there are several different goals expressed in dissimilar units. The overall methodology of MCDA may be described as defining different indicators, which indicates the stakeholders' preferences. Furthermore the relative importances of the different indicators are valued in relation to each other. There are today several methods and models which may be used.

3 A model for evaluation

This chapter describes a model for weighting and evaluation of moisture and energy performance. The model does not specify which specific indicators should be used. The reason is that different stakeholders may prefer different indicators.

3.1 Aggregation of indicators

The overall goal is to evaluate moisture and energy performance. Since there may be a large set of indicators to express one of these, an overall main criteria classification is used for which the indicators are sorted under.

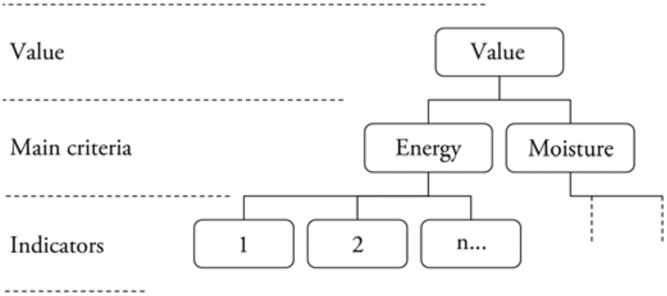


Figure 3.1 General value tree, describing the evaluation model

The aggregation of the indicators follows the AHP method described in Section 2.4.2 (Saaty, 1980). The AHP method is chosen since this method enables relative evaluation between all indicators within each main criterion, as opposed to the swing weight method.

When all indicators to be evaluated have been identified, the indicators are first sorted under the different main criteria. Secondly, within each main criterion, the indicators are pairwise compared according to the scale presented in Table 3.1. Furthermore, the relative importance between energy performance and moisture performance is set, using the same scale.

Table 3.1 Grades used for weighting

Relative importance compared to second indicator	Grade
Equally important	1
More important	3
Much more important	5
Very much more important	7
Extremely more important	9
Less important	3^{-1}
Much less important	5^{-1}
Very much less important	7^{-1}
Extremely less important	9^{-1}

The scale above is based on the "Saaty scale" (Saaty, 1980). The stakeholders may be shown the verbal scale or both the verbal and numerical scale. If the stakeholders hesitate between two alternatives, intermediate values may be used. An example of aggregation of indicators i_1, i_2 and i_3 is presented in Table 3.2a-b. First i_1 is pairwise evaluated in relation to i_2 and i_3, respectively. Thereafter, i_2 is evaluated in relation to i_3 (i_2 is already evaluated in relation to i_1). The relative importance is translated into grades and arranged in an evaluation matrix to calculate the weighting factor, as described in section 2.4.2.

Table 3.2a 3.2a prioritization of indicators using pairwise comparison.

Indicator	Pairwise priority	Indicator
i_1	is *much more important* than	i_2
i_1	is *much less important* than	i_3
i_2	is *less important* than	i_3

Table 3.2b 3.2.b Evaluation matrix and calculated priority

	i_1	i_2	i_3	Weighting factor, *w*
i_1	1	5	5^{-1}	0.26
i_2	5^{-1}	1	3^{-1}	0.10
i_3	5	3	1	0.64

The method described above may be suitable for investigating a limited part of a building envelope, e.g. exterior wall, roof, etc. If a complete building envelope is to be analysed, the main criteria; energy and moisture, may be separated into sub criteria; walls, roof etc. The specific weighting factor, *w*, is the product of the weighting factors of all indicators above in the value tree. If the indicators above were to be energy indicators, and energy is valued equal (weighting factor 0.50) to moisture; all weighting factors are multiplied by 0.50 to receive the specific weighting factor.

3.2 Valuation of indicators

To support the translation of the indicators into relative values, one of the two methods described below may be used, depending on type of indicator and preferences of the stake holder. Following the descriptions and using the different methods, two possible outcomes are presented.

Using the first method, the stakeholders are asked to define levels that are consistent with the value judgements expressed in Table 3.3. The judgements are translated into the relative values presented in the same table. Note: For excellent, the value is set to 120 %. This is done to indicate that excellent is outperforming what is actually required. I.e. a good or very good technical solution, fulfilling the requirements of the stakeholder, does not have to be the best possible solution.

Table 3.3 Values for indicators based on value judgement

Judgement	Value
Excellent	120%
Very good	90%
Good	60%
Fair	30%
Not acceptable	0%

If stakeholders find the first method difficult to apply, the second method may be more suitable. First, a design target is set. The design target should not be equal to a best possible outcome; it should rather reflect the stakeholders' level of what is satisfactory.

Secondly, the best possible outcome is defined, followed by the lowest accepted level. Finally, the threshold for "Not acceptable" is set. These judgements are translated into relative values as presented in Table 3.4.

Table 3.4 Values for indicators based on design target approach

Judgement	Value
Best possible outcome	120%
Design target	100%
Lowest accepted level	1%
Not acceptable	0%

Two possible outcomes, using the different methods, are presented in Figure 3.2. In this case the indicator is energy performance, low/decreasing values are preferred.

Scenario 1, using method 1:

1) "Using more energy than allowed in the building regulations, 90 kWh/m^{2}a, is *not acceptable*". Value = 0%.
2) "Fulfilment of the energy performance set in the building regulations is *fair*". Value = 30%.
3) "Reaching the energy performance of a passive house, 50 kWh/m^{2}a, is *good*". Value = 60%.
4) "Energy performance of 40 kWh/m^{2}a is *very good*". Value = 90%.
5) "Energy performance of 35 kWh/m^{2}a is *excellent*". Value = 120%.

Scenario 2, using method 2:

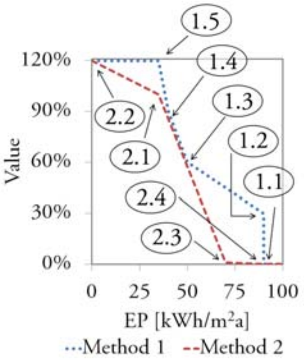
1) "The *design target* is 35 kWh/m^{2}a". Value = 100%.
2) "However, *best possible outcome* is a *Net ZEB*". Value = 120%
3) "*Lowest accepted level* is 75 kWh/m^{2}a" Value 1%
4) "Using more energy than allowed in the building regulations is *not acceptable*". Value = 0%.

The effect of the different methods and scenarios is graphically presented in Figure 3.2.

The result from using the first method indicates that the stakeholder is aware of the increased effort needed to improve the energy performance nearer the judgment of “Excellent”. Taking the step from the requirement in the building regulation, 90 kWh/m^{2}a, to compliance with the energy performance requirement of a passive house, 50 kWh/m^{2}a (Sveriges Centrum för Nollenergihus, 2012), is seen as good. The stakeholder assumes that it is possible to reach this level with a reasonable effort. Taking the step to improve the energy performance by 10 and 5 kWh/m^{2}a, respectively, is seen as increasingly difficult. Hence the first step is 10 kWh/m^{2}a and the second only 5 kWh/m^{2}a.

The second method indicates that the design target is to achieve excellence. However, since it is possible to build *Net ZEBs*, it is possible to outperform the design target and achieve a value of 120%.The lowest acceptable level is 70 kWh/m^{2}a, which is given the value 1%.

Before the model is tested, it is difficult to assess whether any of the methods is better than the other one. Both could be used and the resulting graphs should be used as a basis for discussion.



Method 1
1.1 “Using more energy than allowed in the building regulations = not acceptable”
1.2 ”Fulfilment of the building regulations = Fair”
1.3 “Passive house = good”
1.4 “40 kWh/m a = very good”
1.5 “35 kWh/m a = Excellent”
Method 2
2.1 “The design target is 35 kWh/m a”
2.2 “However, it is possible to build Net ZEB”
2.3 “70 kWh/m a = lowest acceptable level”
2.4 “Using more energy than allowed in the building regulations = not acceptable”

Figure 3.2 *Relative values for indicator; energy performance, using the two different methods*

3.3 Calculating overall value

Before the overall value is calculated, the value of each indicator is calculated.

When the overall value is calculated; a performance failure indicator, k, based on the product of all relative values of the indicators is included, see Equation 3.1.

$$k(a) = 1 \qquad \text{for}\, v_i(a) \cdot \ldots\ldots \cdot v_n(a) > 0$$
$$k(a) = 0 \qquad \text{for}\, v_i(a) \cdot \ldots\ldots \cdot v_n(a) = 0 \qquad \text{Equation 3.1}$$

Where

k(a) The performance failure indicator for alternative *a*
$v_i(a)$ Relative value for criterion *i*, for alternative *a*

The value, *V*, is calculated as shown in Equation 3.2.

$$V(a) = k(a) \cdot \sum_{1}^{i} w_i v_i(a) \qquad \text{Equation 3.2}$$

Where

V(a) The total value of the investigation alternative *a*
k(a) The performance failure indicator for alternative *a*
w_i Weighting factor for indicator *i*, for all alternatives
$v_i(a)$ Relative value for indicator *i*, for alternative *a*

The performance failure indicator was not found in any of the methods studied in the literature review presented in section 2.4.2. The performance failure indicator is intended to prevent sub-optimization. By using the performance failure indicator, alternatives where one or more indicators are at a non-acceptable level receive an overall value of zero, regardless of the value of the other indicators.

Using the example with indicators i_1, i_2 and i_3 weighted as presented above in Table 3.2, a hypothetical input comparing three different alternatives is presented in Table 3.5.

Table 3.5 Relative values for indicators after valuation

	$v_i(a)$	$v_i(b)$	$v_i(c)$
i_1	45%	35%	100%
i_2	100%	30%	0%
i_3	50%	95%	100%

The use of weighting factors and a performance failure indicator has a large impact on the final calculated value. If the relative values for the different indicators were simply summarised, alternative *c* would be the highest valued alternative, with a summarized value of 200%, followed by alternative *a* and lastly alternative *b*. If weighting factors are used, but not the performance failure indicator, alternative c would still receive the highest value. However, alternative b now receives a higher calculated value. The calculated, weighted value is presented below, not using the performance failure indicator.

$$\begin{aligned} w_{i_1} &= 0.26 \\ w_{i_2} &= 0.10 \\ w_{i_3} &= 0.64 \end{aligned}$$

Equation 3.3

$$\begin{aligned} V(a) &= 0.26 \cdot 0.45 + 0.10 \cdot 1.00 + 0.64 \cdot 0.50 = 0.54 = 54\% \\ V(b) &= 0.26 \cdot 0.35 + 0.10 \cdot 0.30 + 0.64 \cdot 0.95 = 0.73 = 73\% \\ V(c) &= 0.26 \cdot 1.00 + 0.10 \cdot 0.00 + 0.64 \cdot 1.00 = 0.90 = 90\% \end{aligned}$$

Equation 3.4

When the performance failure indicator is used, alternative c receives the value of zero and alternative b is now the alternative which receives the highest value, *V*. The relative values for each indicator and alternative together with the calculated value, *V*, using weighting factors and performance failure indicator, are graphically presented in Figure 3.3.

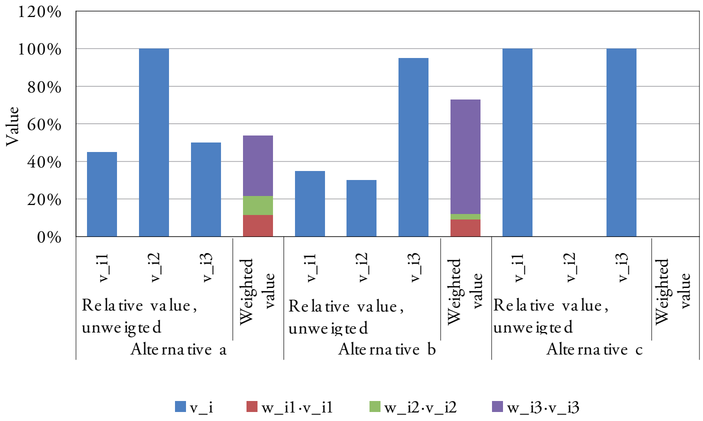


Figure 3.3 *Relative values for the different indicators and the calculated value, V, for all three alternatives*

3.4 Summary

The model described in this section uses the "Saaty scale" for pairwise comparison between different indicators. All indicators are valued in relation to each other. Using an evaluation matrix, the normalized eigenvector of the matrix calculates the weighting factors. Valuation of the different indicators may be done in two different ways where the stakeholders choose to use the method they find easiest to apply. When the overall value of a specific alternative is calculated, weighting the value of the different indicators into one, a performance failure indicator is applied. The performance failure indicator is used to prevent sub-optimization. I.e. it should not be possible, by maximizing the other indicators, to compensate for nonfulfilment of the lowest accepted level by an indicator.

4 Test of the model

This chapter describes two examples of use of the developed model, both for a limited part of a building envelope, and also for a whole building. Input data for the tests are largely based on calculations and simulations carried out in previous investigations presented in Papers II, IV, V and VIII.

4.1 Analysis of limited part of building envelope

4.1.1 Case description

A subcontractor who manufactures prefabricated exterior wooden frame walls is approached by a potential client to deliver exterior walls suitable for a detached single family house, designed to meet the Swedish passive house requirements (Sveriges Centrum för Nollenergihus, 2012). The client has already made a preliminary analysis, indicating that the wall must meet the requirement; $U_c < 0.10$ W/m^{2}K. Before being asked by the potential client, the subcontractor has always delivered exterior walls with a higher U_c; 0.17 W/m^{2}K. Therefore, there is a need to investigate an improved construction.

The subcontractor asks the potential client regarding specific requirements on thermal bridges and moisture safety design. It turns out that the potential client has not considered these parameters. Together, the potential client and the sub contractor define three indicators for the energy performance criteria and two indicators for the moisture performance criteria;

- Energy; thermal transmittance - U_c.
  This was the initial requirement set by the potential client.
- Energy; thermal bridge - exterior corner.
  The final design for the building is not set. However, the junction for the exterior corner needs to be defined as a part of the new exterior wall.
- Energy; thermal bridge - exterior wall-window.
  The final design for the building is not set. However, the architect has specific requirements regarding the aesthetics of the junction between the exterior wall and the window.
- Moisture; general risk of mould growth.
  Hygrothermal simulations for a standard section of the construction are evaluated using the m-model. The investigated point is the exterior part of the wooden frame construction.
- Moisture; analysis of exterior corner.
  The exterior corner is evaluated using the "Hagentoft-model". The risk of onset for mould growth is investigated, as described in section 2.2.3 Critical moisture conditions and assessment of risk of performance failure, at the exterior part of the wooden frame construction.

The subcontractor decides to investigate the indicators for three different alternatives.

- Alternative a – Standard wall.
  An insulated wood frame construction, 170 mm, insulated with mineral wool. Exterior to the wood frame construction; 13 mm wind shield/wind stabilization, 28 mm air gap and wood panel cladding. On the interior side of the wood frame construction; vapour barrier, 70 mm insulated wood frame construction and 13 mm gypsum plasterboard.
- Alternative b – "Traditional approach"
  The increased thermal resistance is achieved by mounting 220 mm of insulation on the interior side of the wood frame construction, followed by the original assembly; vapour barrier, insulated wood frame construction and gypsum plasterboard. This is believed to be the easiest way to increase the thermal resistance.
- Alternative c – Minimizing thermal bridges
  The increased thermal resistance is achieved by mounting 70 mm of insulation on the exterior side of the wood frame construction, and 145 mm of insulation on the interior side. This approach is believed to reduce thermal bridges and decrease the risk of onset of mould growth.

The different wall assemblies are graphically presented in Figure 4.1

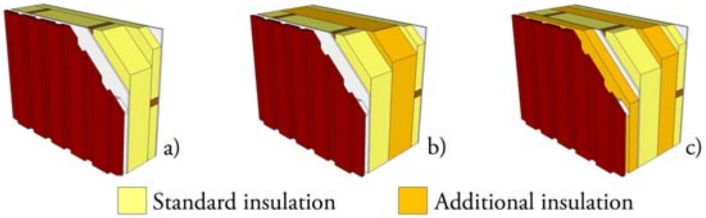


Figure 4.1 *Alternative a; Standard wall construction. Alternative b; Additional insulation on the interior side of the wood frame construction. Alternative c; Additional insulation on the exterior and interior side of wood frame construction.*

4.1.2 Aggregation and evaluation of indicators

Firstly the main criteria and different indicators are pairwise prioritized. The priorities, set up by the potential client, and the resulting weighting factors are presented in Tables 4.1- 4.3 for the criteria- and indicator prioritization separately.

Table 4.1a Prioritization of main criteria

Criteria	Pairwise priority	Criteria
Energy performance	is *more important* than	Moisture performance

Table 4.1b Evaluation matrix and calculated priority of main criteria

	Energy	Moisture	Weighting factor, w
Energy	1	3	0.75
Moisture	3^{-1}	1	0.25

Table 4.2a Prioritization of energy indicators

Indicator	Pairwise priority	Indicator
Thermal transmittance - U_c	is *very much more important* than	Thermal bridge; wall-window
Thermal transmittance - U_c	is *very much more important* than	Thermal bridge; exterior corner
Thermal bridge; wall-window	is *more important* than	Thermal bridge; exterior corner

Table 4.2b Evaluation matrix and calculated weighting of energy indicators

	Thermal transmittance	Thermal bridge; wall-window	Thermal bridge; exterior corner	Weighting factor, *w*
Thermal transmittance	1	7	7	0.77
Thermal bridge; wall-window	7^{-1}	1	3	0.16
Thermal bridge; exterior corner	7^{-1}	3^{-1}	1	0.08

Table 4.3a Prioritization of moisture indicators

Indicator	Pairwise priority	Indicator
General risk of mould growth	is *more important* than	Analysis of exterior corner

Table 4.3b Evaluation matrix and calculated weighting of moisture indicators

	General risk of mould growth	Analysis of exterior corner	Weighting factor, *w*
General risk of mould growth	1	3	0.75
Analysis of exterior corner	3^{-1}	1	0.25

After weighting factors for all indicators and the main criteria have been defined, the specific weighting factors are calculated. The result is presented in Table 4.4.

Table 4.4 Specific weighting factors for indicators

Indicator	Weighting factor, w
Thermal transmittance	0.58
Thermal bridge; wall-window	0.12
Thermal bridge; exterior corner	0.06
General risk of mould growth	0.19
Analysis of exterior corner	0.06

Secondly, the relative values of the indicators are addressed. The relative values for moisture indicators are determined by using the method of stating a design target, followed by defining best possible outcome, lowest accepted level and threshold for "Not acceptable". The same method is used to value the thermal transmittance indicator. The relative values for the thermal bridges are valued using the second option. Values are defined by defining excellent, very good, good, fair, and not acceptable. Relative values for energy- and moisture indicators are presented in Figure 4.2 and Figure 4.3 respectively.

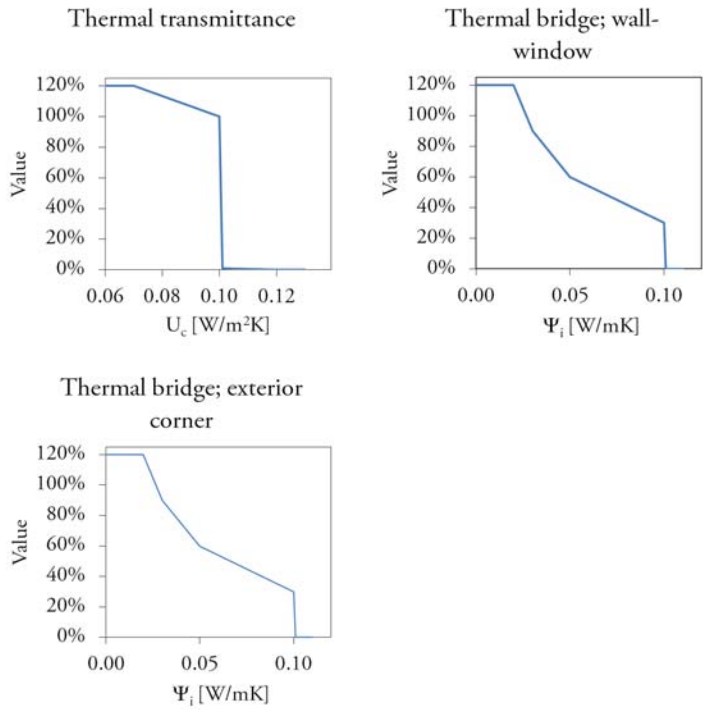


Figure 4.2 Relative values for energy indicators

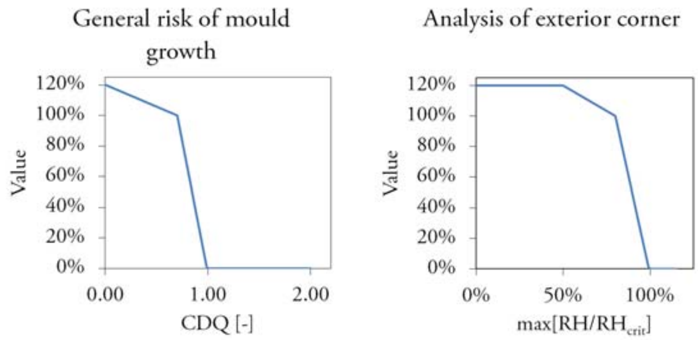


Figure 4.3 Relative values for moisture indicators

4.1.3 Results from the analysis

The quantified result and the relative value of the indicators are presented in Table 4.5. It should be noted that if the relative value is larger than 100%, the design target is outperformed.

Table 4.5 Quantified result and the relative value of indicators

		Alternative a	Alternative b	Alternative c
Thermal transmittance	Quantified result	0.170	0.085	0.085
	Relative value	0%	106%	106%
Thermal bridge; wall-window	Quantified result	0.026	0.043	0.030
	Relative value	102%	71%	90%
Thermal bridge; exterior corner	Quantified result	0.058	0.027	0.028
	Relative value	55%	100%	96%
General risk of mould growth	Quantified result	0.29	1.34	0.37
	Relative value	85%	0%	76%
Analysis of exterior corner	Quantified result	98%	98%	94%
	Relative value	2%	2%	7%

The relative values and the weighted value are presented in Figure 4.4. The value of each indicator is not weighted, meaning that only the relative value, based on Figure 4.2 and Figure 4.3, is presented. The weighted value is the sum of the value of each indicator multiplied by the specific weighting and the performance failure indicator.

Some consequences of the results are worth noting; *Alternative a* receives the highest relative value when the risk of mould growth is analysed (the risk of mould growth is low). However, since failing to fulfil the most important indicator, thermal transmittance (U_c); the weighted value is 0. *Alternative b* fulfils the requirement regarding thermal transmittance, but fails to fulfil the requirement regarding risk of mould growth; the weighted value is 0. *Alternative c* is the only construction that receives a weighted value. Hence, it is the only construction that does not get a relative value equal to 0% for any indicator.

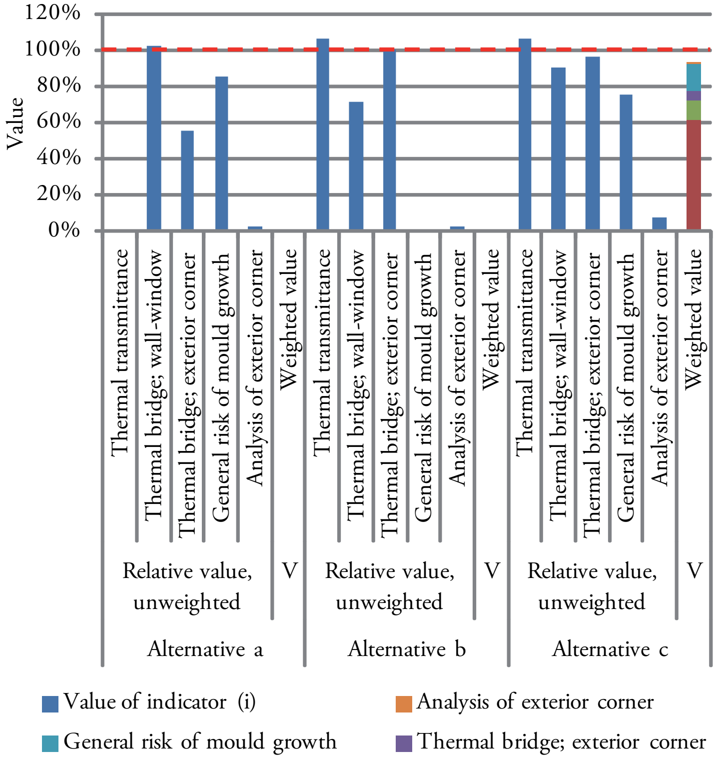


Figure 4.4 *Results from the analysis of different wall assemblies. The red line represents the design target. Note that higher values are always better. E.g. high value of the indicator "General risk of mould growth" means that the risk is low.*

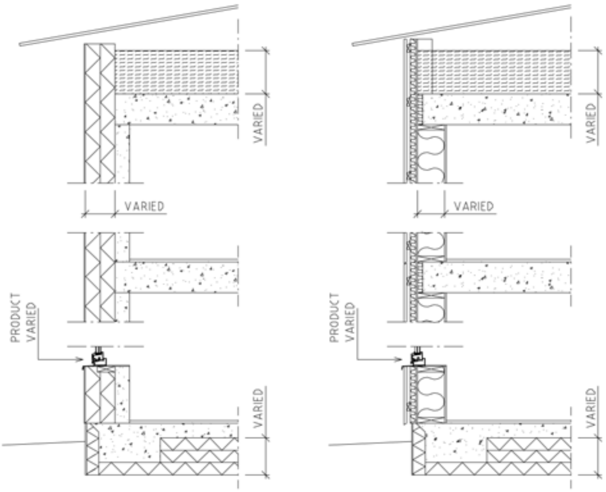
4.2 Analysis of the whole building system

4.2.1 Case description

A contractor and a client discuss the choice of building system for a multi-dwelling building. The focus is on exterior walls and the choice is between concrete walls with external insulation or infill walls; insulated wooden frame walls. Furthermore, the client wishes to investigate two options; standard building and low-energy building. U-values for the building envelope are presented in Table 4.6. For all cases, balanced ventilation with heat recovery η=80% is installed. General descriptions of the building systems are presented in Figure 4.5.

Table 4.6 Different levels of U-values used

Construction	U-values for different building categories (W/m^{2}K) Standard building	Low-energy building
Floor slab on ground	0.17	0.09
Roof	0.12	0.08
External walls	0.20	0.09
Windows/ doors	1.50	0.90



CONCRETE WALLS WITH EXTERNAL INSULATION

WOODEN FRAME WALLS WITH INSULATION

Figure 4.5 Generic descriptions of investigated building systems

To evaluate the two choices, the following indicators are agreed upon:

- Energy; thermal transmittance - U_c.
  U_c-values for each building element.
- Energy; average U-value of the building, including thermal bridges. Since the architectural design of the building is set, the total transmission heat transfer coefficient, including thermal bridges, divided by the enclosing area, is evaluated
- Energy; energy performance.

The annual energy need for space heating, divided by conditioned area, is included.
- Energy; peak load for space heating
- Energy; embodied energy
- Moisture; Mould index.
  A hygrothermal simulation for a standard section of each exterior wall construction is carried out and analysed using WUFI Bio.
- Moisture; Analysis of junctions.
  The following junctions are evaluated using the "Hagentoft-model";
  - Floor slab on ground – exterior wall
  - Intermediate floor – external wall
  - Attic slab – exterior wall

  For each junction, critical levels for onset of mould growth according to (Johansson et al., 2005) and performance failure according to (Nilsson, 2006) are investigated.

4.2.2 Aggregation and evaluation of indicators

To facilitate the large number of indicators, abbreviations in Table 4.7 are used.

Table 4.7 Abbreviations used for the different indicators

Main criteria	Indicator	Evaluation unit	Abbreviation
Energy	U_c, slab on ground	[W/m^{2}K]	E1
	U_c, external wall	[W/m^{2}K]	E2
	U_c, windows/doors	[W/m^{2}K]	E3
	U_c, roof construction	[W/m^{2}K]	E4
	Average U-value	[W/m^{2}K]	E5
	Energy performance	[kWh/m^{2}a]	E6
	Peak load for space heating	[W/m^2]	E7
	Embodied energy	[MJ/m^{2}a]	E8
Moisture	Mould index	[-]	M1
	Junction; Floor slab on ground – exterior wal	max[RH/RH$_{crit}$]	M2
	Junction; Intermediate floor – external wall	max[RH/RH$_{crit}$]	M3
	Junction; Attic slab – exterior wall	max[RH/RH$_{crit}$]	M4

The client and the contractor discuss the overall main criteria; Energy performance and moisture performance. They agree that they are equally important. Hence, they are given the weighting factors 0.50, see Table 4.8a-b.

Table 4.8a Prioritization of main criteria

Criteria	Pairwise priority	Criteria
Energy performance	*equally important*	Moisture performance

Table 4.8b Evaluation matrix and calculated priority of main criteria

	Energy	Moisture	Weighting factor, *w*
Energy	1	1	0.50
Moisture	1	1	0.50

After the main criteria are defined, all indicators are valued pairwise in relation to each other. The prioritizations, evaluation matrixes and results are presented in Table 4.9a-b and Table 4.10a-b.

Table 4.9a Prioritization of energy indicators

Indicator	Pairwise priority	Indicator
E_1 U_c, slab on ground	*Equally important*	E_2 U_c, external wall
E_1 U_c, slab on ground	*More important*	E_3 U_c, windows/doors
E_1 U_c, slab on ground	*Equally important*	E_4 U_c, roof construction
E_1 U_c, slab on ground	*Strongly less important*	E_5 Average U-value
E_1 U_c, slab on ground	*Strongly less important*	E_6 Energy performance
E_1 U_c, slab on ground	*Less important*	E_7 Peak load for space heating
E_1 U_c, slab on ground	*Less important*	E_8 Embodied energy
E_2 U_c, external wall	*More important*	E_3 U_c, windows/doors
E_2 U_c, external wall	*Equally important*	E_4 U_c, roof construction
E_2 U_c, external wall	*Strongly less important*	E_5 Average U-value
E_2 U_c, external wall	*Strongly less important*	E_6 Energy performance
E_2 U_c, external wall	*Less important*	E_7 Peak load for space heating
E_2 U_c, external wall	*Less important*	E_8 Embodied energy
E_3 U_c, windows/doors	*Less important*	E_4 Uc, roof construction
E_3 U_c, windows/doors	*Strongly less important*	E_5 Average U-value
E_3 U_c, windows/doors	*Strongly less important*	E_6 Energy performance
E_3 U_c, windows/doors	*Less important*	E_7 Peak load for space heating
E_3 U_c, windows/doors	*Less important*	E_8 Embodied energy
E_4 U_c, roof construction	*Strongly less important*	E_5 Average U-value
E_4 U_c, roof construction	*Strongly less important*	E_6 Energy performance
E_4 U_c, roof construction	*Less important*	E_7 Peak load for space heating
E_4 U_c, roof construction	*Less important*	E_8 Embodied energy
E_5 Average U-value	*More important*	E_6 Energy performance
E_5 Average U-value	*More important*	E_7 Peak load for space heating
E_5 Average U-value	*Strongly more important*	E_8 Embodied energy
E_6 Energy performance	*Less important*	E_7 Peak load for space heating
E_6 Energy performance	*More important*	E_8 Embodied energy
E_7 Peak load for space heating	*More important*	E_8 Embodied energy

Table 4.9b Evaluation matrix and calculated priority of energy indicators

	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8	Weighting factor, *w*
E_1	1	1	3	1	5^{-1}	5^{-1}	3^{-1}	3^{-1}	0.05
E_2	1	1	3	1	5^{-1}	5-1	3^{-1}	3^{-1}	0.05
E_3	3^{-1}	3^{-1}	1	1	5^{-1}	5^{-1}	3^{-1}	3^{-1}	0.03
E_4	1	1	3	1	5^{-1}	5^{-1}	3^{-1}	3^{-1}	0.05
E_5	5	5	5	5	1	3	3	5	0.33
E_6	5	5	5	5	3^{-1}	1	3^{-1}	3	0.18
E_7	3	3	3	3	3^{-1}	3	1	3	0.20
E_8	3	3	3	3	5^{-1}	3^{-1}	3^{-1}	1	0.10

Table 4.10a Prioritization of moisture indicators

Indicator	Pairwise priority	Indicator
M_1 Mould index	*More important*	M_2 Junction; Floor slab – wall
M_1 Mould index	*More important*	M_3 Junction; Intermediate floor – wall
M_1 Mould index	*More important*	M_4 Junction; Attic slab – wall
M_2 Junction; Floor slab – wall	*Equally important*	M_3 Junction; Intermediate floor – wall
M_2 Junction; Floor slab – wall	*Equally important*	M_4 Junction; Attic slab – wall
M_3 Junction; Intermediate floor – wall	*Equally important*	M_4 Junction; Attic slab – wall

Table 4.10b Evaluation matrix and calculated priority of moisture indicators

	M_1	M_2	M_3	M_4	Weighting factor, *w*
M_1	1	3	3	3	0.50
M_2	3^{-1}	1	1	1	0.17
M_3	3^{-1}	1	1	1	0.17
M_4	3^{-1}	1	1	1	0.17

After the main criteria and indicators are relatively valued, the specific weighting factors are calculated. The result is presented in Table 4.11, which presents the indicators ranked, based on the specific weighting factor. As can be seen, the mould index is given the highest specific weighting factor. Windows and doors are given the lowest specific weighting factor. This reflects the client's concerns about moisture safety design and thoughts that it is relatively easy to replace windows and doors during the operation phase.

Table 4.11 Weighting factors for indicators

Indicator	Weighting factor, *w*
M_1 Mould index	0.25
E_5 Average U-value	0.17
E_7 Peak load for space heating	0.10
E_6 Energy performance	0.09
M_2 Junction; Floor slab – wall	0.09
M_3 Junction; Intermediate floor – wall	0.09
M_4 Junction; Attic slab – wall	0.09
E_8 Embodied energy	0.05
E_1 U_c, slab on ground	0.03
E_2 U_c, external wall	0.03
E_4 U_c, roof construction	0.03
E_3 U_c, windows/doors	0.02

All indicators are valued with reference to a chosen design target followed by the best possible outcome and lowest accepted level. The result is presented in Figure 4.6 - 4.8.

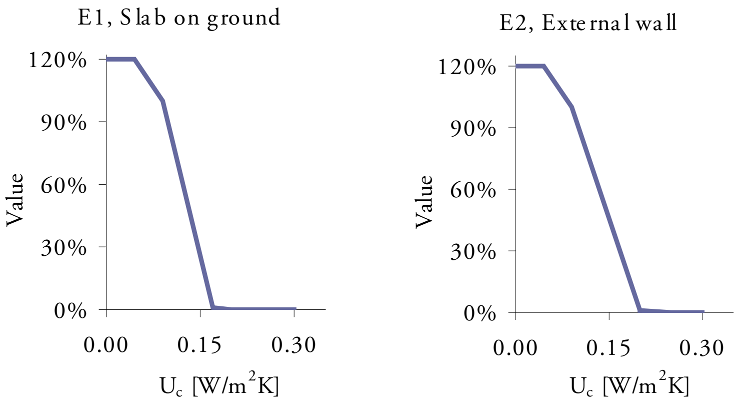


Figure 4.6 Relative values for all indicators

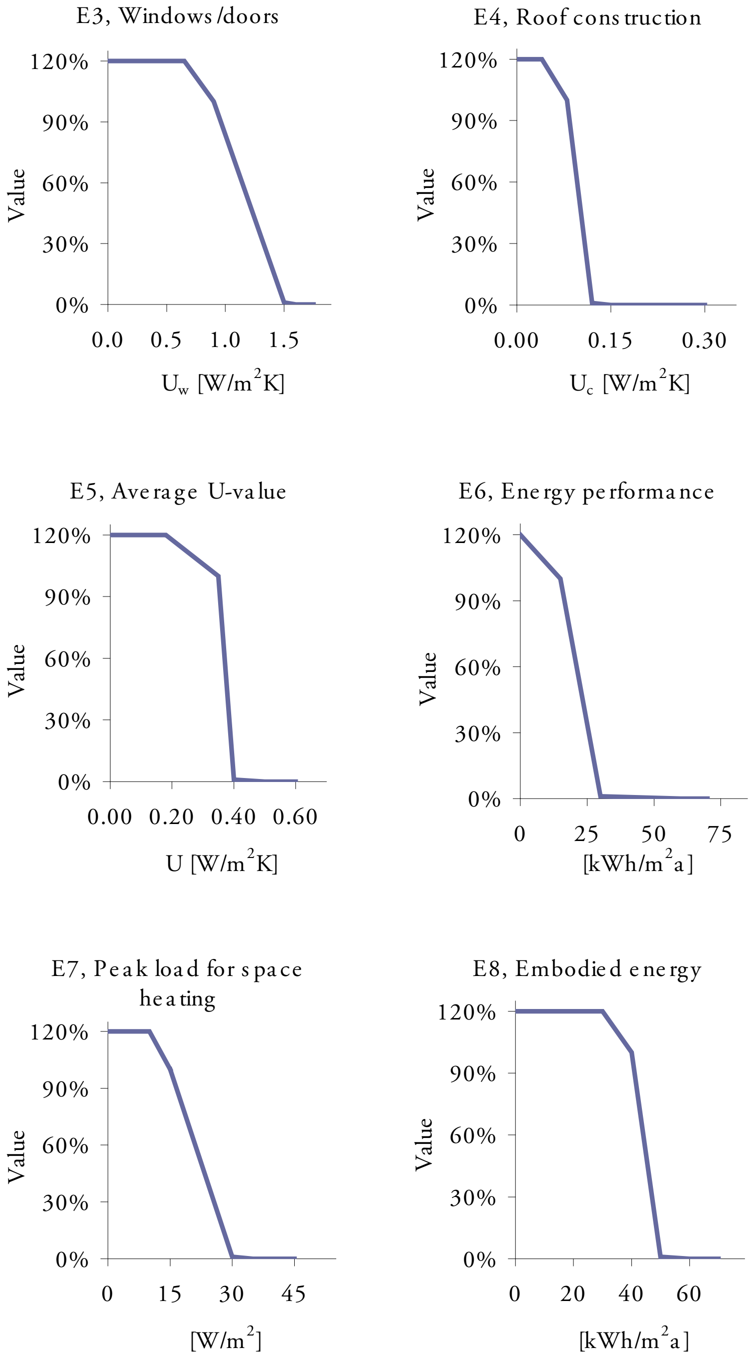


Figure 4.7 Relative values for all indicators

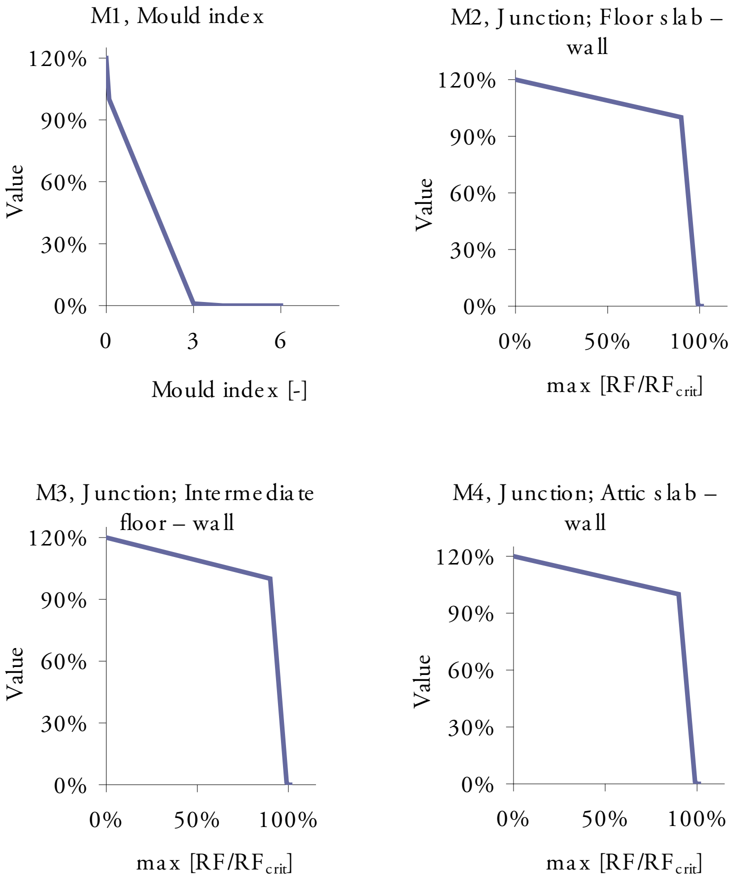


Figure 4.8 Relative values for all indicators

4.2.3 Result of the analysis

In Table 4.12, the quantified result is presented together with the weighted value. In this case study the client misjudged the effect of thermal bridges and windows. The client expected that by using building elements at a lowest accepted level, the average U-value (E_5) would be 0.40 W/m^{2}K. However, due to the low number of windows and lower thermal bridges than expected; all alternatives outperform the design target of 0.35 W/m^{2}K. The design targets for annual energy need for space heating and peak load for heating (E_6 and E_7) are reached for the low-energy building, regardless of building system. The only energy indicator, for the low-energy building systems, which does not reach the design target, is the embodied energy (E_8).

When the two low-energy alternatives are compared, only considering energy indicators, the wooden frame wall alternative would get a somewhat higher value regardless of the fact that the concrete alternative receives a higher value for indicators E_5, E_6 and E_7 (average U-value, energy performance and peak load for heating). This is due to the higher quantity of embodied energy in the concrete walls (E_8).

No alternative reaches the design target of the mould index, which was set to 0.1. However, no alternative reaches mould index 3 which indicates visible mould growth. When the different alternatives are compared, only examining moisture indicators, the standard building with concrete walls receives the highest value, followed by the low-energy building with concrete walls.

Table 4.12 Quantified result and the relative value of indicators

		Standard building		Low-energy building	
		Concrete walls	Wooden frame walls	Concrete walls	Wooden frame walls
E_1	Quantified result	0.17	0.17	0.09	0.09
	Relative value	1%	1%	100%	100%
E_2	Quantified result	0.20	0.20	0.09	0.09
	Relative value	1%	1%	100%	100%
E_3	Quantified result	1.50	1.50	0.90	0.90
	Relative value	1%	1%	100%	100%
E_4	Quantified result	0.12	0.12	0.08	0.08
	Relative value	1%	1%	100%	100%
E_5	Quantified result	0.31	0.33	0.19	0.21
	Relative value	104%	102%	118%	116%
E_6	Quantified result	29	30	14	15
	Relative value	8%	1%	101%	100%
E_7	Quantified result	19	20	13	14
	Relative value	77%	66%	109%	104%
E_8	Quantified result	37	35	43	41
	Relative value	105%	110%	66%	89%
M_1	Quantified result	0.9	1.8	1.5	2.3
	Relative value	70%	41%	51%	24%
M_2	Quantified result	90%	92%	93%	95%
	Relative value	100 %	78%	67%	45%
M_3	Quantified result	92%	95%	91%	99%
	Relative value	78%	45%	89%	1%
M_4	Quantified result	91%	94%	92%	97%
	Relative value	89%	62%	78%	23%

In Figure 4.9 and 4.10, the values of all indicators together with the weighted value are presented. No indicator was below the lowest accepted level. Hence, the performance failure indicator is equal to 1 for all alternatives, and all alternatives receive a weighted value. The alternative which received the highest value considering energy indicators, the low-energy building with wood construction, does not receive the highest weighted value due to the lower value considering moisture indicators. Furthermore, the alternative which received the highest value considering moisture, the standard building with concrete construction, does not receive the highest value. The low-energy building with concrete construction receives the highest weighted value.

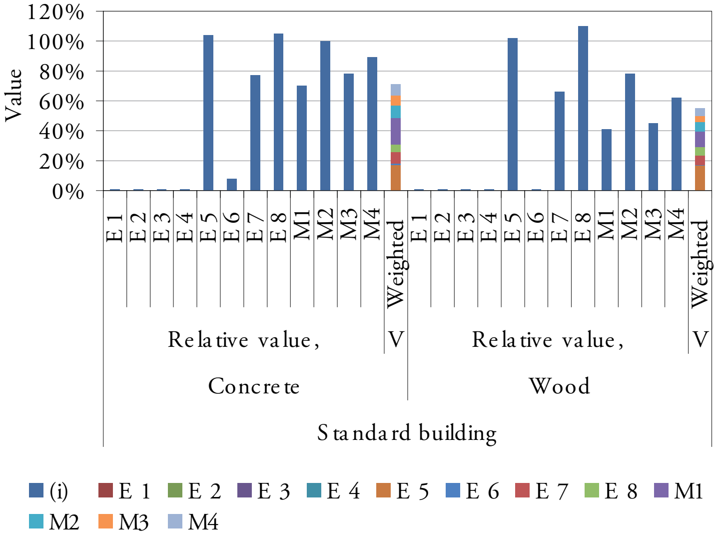


Figure 4.9 *Result from analysis of different wall assemblies, standard building*

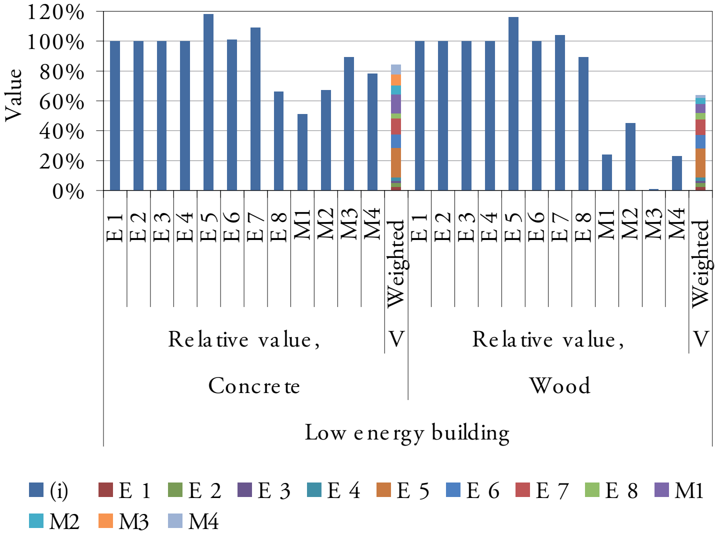


Figure 4.10 *Result from analysis of different wall assemblies, low energy building*

4.3 Summary

The model described in Section 3 has been tested for two different case studies. The analysis of a limited part of the building envelope resulted in only one alternative receiving a weighted value due to the use of performance failure indicator.

In the second analysis where an analysis of whole building systems was conducted, all comply with the lowest accepted level. Hence, all alternatives receive a weighted value. None of the alternatives that received the highest value considering energy indicators or moisture indicators received the highest weighted value.

5 Discussion and conclusions

This chapter discusses the research carried out. General research questions which need more investigations are highlighted and focus of the continuation of this work and further use of the model is presented.

5.1 Energy performance

The term: "energy performance" of buildings is today often communicated in north European countries, and it is generally alleged that it refers to annual energy use per conditioned living area. This was not the case in the beginning of this millennium. However, since 2012 when Finland updated its building regulations, Denmark, Finland, Norway and Sweden all have requirements regarding energy performance in the building regulations. The literature review also shows that energy performance is a common indicator in environmental indicator systems. Net Zero Energy Buildings, *Net ZEBs*, is a rather new concept, but there is an increasing number of projects all over the world; showing that it is possible for a building to cover its annual energy demand by renewable energy supply, often on-site.

Differences occur in the definitions, both regarding energy performance and *Net ZEB*. To enhance knowledge transfer and to increase exchange of experiences and new ideas between countries, more harmonised requirements in building regulations could be one measure. Harmonising requirements and definitions may be a difficult and time-consuming task. As a first step it is recommended that the definition framework, presented by the joint research task; IEA SHC Task 40/ECBS Annex 52, is used.

Even though calculation of transmission heat transfer is well defined in international standards, the state of knowledge among Swedish engineers and architects regarding different measuring methods and the effect on thermal bridges is not satisfactory. This is alarming. If a junction is not seen as a potential thermal bridge, it is not likely that any analysis will be carried out to investigate the effect on thermal transmission by the specific junction. Furthermore, no prevailing method regarding measurement, applied by engineers and architects, can be identified. A need for clearer building regulations, development of guidelines regarding the way the available international standards should be used and need for education/ training of engineers and architects has been identified.

The literature review and detailed study of embodied energy showed that there is a tenuous trend indicating that the embodied energy in new construction is decreasing. However, the embodied energy as the relative share of the total energy use throughout the whole life cycle is increasing. In studies that clearly reported embodied energy broken down into different parts of the building; load bearing constructions, installations, etc., the main contributor to the embodied energy is materials used within the building envelope and load bearing constructions. Hence, there is a need to raise the awareness of embodied energy. Especially when building envelopes and load bearing constructions for low-energy buildings, passive houses and *Net ZEBs* are considered. Today, there is no international definition regarding the way embodied energy is to be calculated. Furthermore, it is unusual to include requirements regarding embodied energy in environmental indicator systems.

5.2 Moisture performance

There is no international or European standard for assessing and presenting moisture performance. When the building regulations in Denmark, Finland, Norway and Sweden are reviewed, only Sweden sets a quantified level for moisture safety design. For the other countries the requirements are more functional and generally state that buildings should be designed not to suffer from performance failure due to hygrothermal conditions. Denmark, however, has extensive guidelines for assessing the risk of performance failure due to hygrothermal conditions.

Within the literature review, critical levels for onset of mould growth, corrosion, rot, cementation reactions etc. were found. However, these were based on steady-state conditions. In reality, the hygrothermal conditions are fluctuating. Hence there is a need for improvement and increased use of models to investigate the risk of performance failure. To take the fluctuating conditions into consideration, four different models were examined and tested to evaluate the risk of performance failure due to hygrothermal conditions.

Comparing energy performance and moisture performance and/or moisture safety design, there are two important differences to be aware of:

- Energy performance of buildings and building elements is almost without exception expressed in quantitative terms. Moisture performance and/or moisture safety design of buildings and building elements are often based on experience. The experiences are often expressed qualitatively, and not specified in quantitative terms.
- As regards energy performance; a junction, connecting two building elements, may have poor insulation. This creates a relatively large thermal bridge, degrading the energy performance. However, this may be compensated for by improving other parts of the building; using/adding more insulation, installing better windows, more energy efficient HVAC-system etc. A poorly designed junction, resulting in damaging amounts of moisture entering the building envelope, may affect the whole building regardless of how good the rest of the design is.

Based on the statements above it can be concluded that there is a need for improvement and increased use of models to investigate the risk of performance failure related to moisture. Furthermore, the evaluations may be conducted in a different way; analysing the “weak links” in a construction design instead of evaluating the whole building envelope.

Within the building construction industry, robustness and durability of building elements are often based on experience, expressed in quantitative terms. Therefore, it may be difficult to compare and analyze different solutions. Hence there is a need for improvement and increased use of models to investigate the risk of performance failure.

5.3 Future Boundary conditions

There is a warming of the global climate system. Initial simulations considering a future climate scenario show that the risk of mould growth increases. Hence, there is a need to consider future boundary conditions when the risk of performance failure due to hygrothermal conditions is investigated. Within this study, simulations of energy performance based on future climate scenarios have not been conducted. However, the energy needed for heating of dwellings will be affected by the climate change.

Often when simulations are conducted to investigate space heating demand of a dwelling, constant internal heat gain loads due to occupancy and the use of electric equipment are assumed. Recent publications have documented the varying use of electronic equipment and occupancy and also tested the impact of constant and varying loads. The daily variation has a small impact on the annual energy performance compared to seasonal variation. However, the daily variation is important if the grid interaction and load cover of energy generated from solar or wind on site is investigated.

5.4 Multi Criteria Decision Analysis – MCDA

MCDA helps stakeholders to manage subjectivity and to integrate objective/quantitative and value judgement, but will not produce a "right answer" or an optimum. Many different methods exist. The standardized ASTM method where all indicators are pairwise compared has the benefit of being consistent if the indicators already are quantified. The disadvantage is that no indicator will receive a value of zero, which indirectly means that all options/solutions are accepted. Using a value scale, where different levels of an indicator are graded and transformed into a value, enables a stakeholder to define a threshold for the unacceptable. Indicators may then receive a value of zero if the level is not accepted. Regarding weighting of the different values into one weighted value, the swing weight method is much easier to use than the Analytic Hierarchy Process, AHP. The advantage of the AHP method is that all indicators are valued pairwise against each other. Using the swing weight method, all indicators are compared with one, the most important, indicator.

In a way, MCDA is already commonly used today as different environmental indicator systems are usually examples of MCDA. However, as the review shows, the value and weighting of different indicators are already defined. I.e. the environmental indicator systems may not reflect stakeholders' preferences and value judgement.

5.5 Model for evaluation

The objective of this research was to identify a methodology to evaluate building envelopes, taking energy and moisture performance into consideration. A model is proposed, taking energy and moisture performance into account. As the literature review of energy and moisture performance showed, these may be expressed in many different ways. Therefore, the model does not specify which specific indicators should be used.

The chosen approach to weight different indicators is the Analytic Hierarchy Process, AHP. The method is more complex compared to the swing weight method. However, the advantage is that all indicators are valued relatively to each other.

The transformation of the indicators into a value is managed by defining different levels from not acceptable to excellent or best possible outcome. This method is chosen over the ASTM method since the result may be the indicator receiving a value of zero, which means that the option/solution is not accepted. When all values are weighted together, based on AHP, the performance failure indicator reduces the risk for sub optimisation. It should be noted that it would not have been possible to use the performance failure indicator if the ASTM method had been used.

The tests of the model showed that it is possible to handle a large set of criteria and to weight them into one value. Hence the model should make it easier to take informed decisions based on a large set of criteria.

Testing the model, some major conclusions have been made:

1. When the pairwise priority had been made for the main criteria and the indicators, the specific weighting factors were calculated and ranked. Presentation of the ranking may be useful. It enables stakeholders to reflect on the effect of their priorities.
2. When many indicators are valued and presented at the same time, it will be quite cluttered and difficult to interpret the result. This may be managed by dividing the main criteria; energy and moisture, into different sub criteria. The presentation of the results could then be filtered by the different criteria and indicators. E.g. one stakeholder may initially only be interested in the weighted value. However, realising that a certain alternative receives a low value for the energy criterion, the stakeholder may wish to investigate and compare the values of each indicator within that specific criterion.
3. Within this study, most of the work was done manually and was quite time consuming. Most likely there are plenty of different computer programs available to support these kinds of MCDA.

5.6 Future research

5.6.1 Future research within this project

Within this project the future research will focus on:

- Building envelopes:
  A historical review of building envelopes together with projects considered to be best practice will be conducted. The specific and relative effects of transmission heat transfer losses though different building elements and thermal bridges will be investigated in order to identify which measures could have the largest effect on reducing the transmission heat transfer losses.
- Future climate:
  Climate files for different climate scenarios will be created in order to enable investigations of the effect of climate change, both in the existing building stock and in new construction.
- Further tests of the evaluation model:
  The developed model will be tested using different climate scenarios for the existing building stock and new construction. The tests will focus on improvements in usability and how results can be presented. This will be carried out in order to facilitate beneficial use of the model within the building construction industry.

5.6.2 Other aspects of interest

Other aspects of interest, which will not be included in the continuation of this research project, are presented below.

Energy performance

- Today, there is no international standardised calculation method to include the effect of natural convection in insulation. More research is needed to investigate the effect of natural convection in insulation and how to account for its effects on transmission heat transfer through building elements.
- The concept of *Net ZEB* is still rather new in Sweden. The existing definition may need to be further defined, especially considering how to evaluate and account for the impact on the energy infrastructure. The research should be conducted in collaboration with stakeholders representing the Nordic energy infrastructure.
- Embodied energy as a relative share of the total energy use during the life cycle of a building is increasing. There is a need to develop a trans-

parent database and calculation methodology for embodied energy in materials and products.

Moisture performance

- Moisture performance and moisture safety design are seldom expressed in quantitative terms. Development of a rating similar to energy labelling would enable stakeholders to compare different building elements or buildings in a simple way. Furthermore it may increase the interest in moisture safe buildings.
- Today, there are methods and models developed to investigate the risk of mould growth on and in constructions, considering fluctuating hygrothermal conditions. More research for other changes such as corrosion, carbonation, alkali reactions etc. should be developed.
- The “Dose model” and the “m-model” described in this thesis are only to some extent validated. More research considering validation of these models is needed.

Future boundary conditions

- Different standards and publications specify different indoor climate conditions and requirements. Further studies should investigate the effect of these on energy- and moisture performance.

Multi Criteria Decision Analysis – MCDA

- More studies may be conducted to investigate why MCDA is not used more within the building construction industry, in order to find barriers and measures to overcome these.

Model for evaluation

- Computer tools available to carry out MCDA should be investigated in order to find a suitable alternative that can handle the evaluation model described in this thesis.
- The developed model should be tested in real projects in order to gather feedback and enable improvements.

Summary

Energy use of buildings worldwide accounts for more than 40% of the primary energy use and almost one quarter of the greenhouse gas emissions. As the world's population and need for buildings increases, reduction of energy use and increased use of energy from renewable sources within the building sector represents important measures for climate mitigation.

It is essential that the world tries to keep the warming below 2°C. If the temperature increases more, it may lead to irreversible impacts, such as coastal flooding and extinction of species, and billions of people risk to suffer from water shortage. This is recognised by the European Parliament, EU, which has adopted the Energy Performance of Buildings Directive (EPBD).

The directive declares that all member states shall make sure that by 31 December 2020; all new buildings are nearly zero-energy buildings, i.e. buildings with a very high energy performance and nearly the zero amount of energy required should be covered to a very significant extent by renewable energy. The directive also states that buildings that undergo major renovation shall be upgraded to meet a minimum level of energy performance set by the member state. By the year 2013, at the latest, member states shall adopt and publish laws and regulations to comply with the directive.

Common measures for improving the energy performance of buildings in a cold climate are increased thermal resistance and improved airtightness. However, increased thermal resistance of the building envelope will result in different hygrothermal conditions within the building envelope; the outer parts of a wall will have conditions more similar to the exterior climate and moisture may take a longer time to dry out.

Unfortunately, the building sector has a history of sometimes testing new technologies for the building envelope without considering all the possible effects and relying on rule of thumb and experience. Hence, there is a need to develop robust building envelopes that can meet future demands for energy efficiency throughout their life cycle, with moisture safety valued as an important factor in the evaluation and with future climate scenarios considered.

The objective of this research was to identify a methodology to evaluate building envelopes, taking energy and moisture performance into account. The research focuses on building envelopes for residential buildings in a Nordic climate, concentrating on the north European countries; Denmark, Finland, Norway and Sweden.

A literature review was conducted to investigate how moisture conditions and energy performance may be evaluated and calculated today. Also, publications concerning Multi-Criteria Decision-Making, MCDM, and climate change were reviewed. Various case studies were conducted during the project in order to gather knowledge and experience of the different calculations and evaluation methodologies.

A method to evaluate energy and moisture performance, based on MCDM, was developed and tested. The method for evaluation does not claim to be able to judge whether a design will or will not withstand future climate. It will primarily be suitable for comparing energy performance and moisture safety between different technical solutions.

Regarding energy performance, it is important to clarify definitions and boundary conditions. When reference is made to energy performance of buildings, it is generally assumed that one is referring to annual operating energy use, divided by the conditioned area. If renewable energy generation is used to compensate for the energy demand, the building may be referred to as a Zero Energy Building, *ZEB*, or Net Zero Energy Building, *Net ZEB*. Although the terms energy performance, *ZEB* and *Net ZEB* are commonly used, there may be differences between different countries. Common differences are how the boundary conditions are defined, if/how weighting systems are used to account for different energy sources, what energy uses are included etc.

Within the examined environmental indicator systems, annual energy use per conditioned living area is the most common indicator. To enhance knowledge transfer and to increase exchange of experiences and new ideas between countries, more harmonised requirements in building regulations could be necessary.

To ensure a low heating demand for residential buildings in Nordic climates, a building envelope with low transmission heat transfer losses is fundamental. Calculation methodologies taking into account transmission heat transfer through the building envelope, including thermal transmittance through building elements and thermal bridges, are well defined within international standards. However, quantification of the building elements and thermal bridges may be measured according to one of the three methods; internal, overall internal or external dimensions. This creates opportunities for misunderstandings and misinterpretations, which could lead to errors in estimating energy losses.

Within this study, a survey was conducted which shows that the state of knowledge among Swedish engineers and architects is too low and that simplified methods are often used to account for thermal bridges. The relative impact of thermal bridges increases when the thermal resistance of the building envelope increases. The use of simplified methods, such as accounting for thermal bridges by increasing U-values for building envelopes by a fixed percentage, is not suitable.

Embodied energy and life cycle energy analysis of buildings was also studied. Analysis of energy use throughout the life cycle, Life Cycle Energy (*LCE*), of a building is still a rather new topic. When referring to *LCE* it is common to include:

- Energy use for production, construction and renovation of buildings during the life cycle, embodied energy (*EE*).
- Energy consumed to maintain the desired indoor environment, operating energy (*OE*).
- Energy required and recycled when a building is demolished, demolition energy (*DE*).

As for the definition of energy performance of *ZEBs* and *Net ZEBs*, it is possible to distinguish areas where the definitions and calculations methodologies differ. Usually, differences may be found within the metric of balance, life span assumed, boundary conditions, age of data and data source. When the *LCE* is analysed , the focus should be on energy used during the construction and operating phases of the building. Energy used for demolition is usually less than 1% of the *LCE*. When previous studies are compared, there is a small decrease in embodied energy, *EE*. However, *EE* as a relative share of the total life cycle energy, *LCE*, is increasing as the *OE* is decreasing. The main contributor to the EE is materials used within the building envelope and load bearing constructions.

There is no general and commonly used definition of moisture performance, unlike the term energy performance, which is relatively well defined and known to engineers and architects. Moisture performance may refer to hygrothermal characteristics of a material or risk of performance failure due to exceeding critical hygrothermal conditions. Also, there is no international or European standard for assessing and presenting moisture performance. The legal requirements regarding moisture safety design differ in the reviewed north European countries. Only Sweden sets a quantified level for moisture safety design. If the critical moisture level for a material is not well-researched and documented, the building regulations states that a RH_{crit} of 75% shall be used. In Denmark, Finland and Norway the requirements are more functional and generally state that buildings should be designed not to suffer from performance failure due to hygrothermal conditions. Denmark, however, has extensive guidelines for assessing the risk of performance failure due to hygrothermal conditions.

Hygrothermal conditions for changes in materials or onset of mould growth on materials are different for different materials. Furthermore, the duration of a specific hygrothermal condition is important. Since the hygrothermal conditions in the outdoor climate, indoor climate and within building elements are fluctuating, there is a need to use evaluation models that may show the risk of performance failure, considering fluctuating hygrothermal conditions. Within this study four different models were examined and tested.

The model referred to as the “Hagentoft-model” is rather simple and straightforward to use. However, as it is based on monthly averages of temperature and RH, the model does not consider short periods of extreme weather conditions. The “Dose-model” and the “m-model” are more complex compared to the “Hagentoft-model” but still easy enough to use in a simple tool, e.g. MS Excel. The “m-model” is somewhat more complex due to the use of hourly data compared to daily averages in the “Dose-model”. The “Dose-model” and the “m-model” are developed to investigate the risk of mould growth on wood. These models are limited compared to the “Hagentoft-model” which may be used to check RH_{crit} for other changes such as corrosion, swelling etc. The software WUFI Bio may be used in different ways. Once a simulation is carried out using WUFI, or data is imported via a text file, it is easy to investigate the risk of mould growth for different substrate classes using WUFI Bio.

There are also different methods to generate input data for outdoor climate, considering climate change. The imposed offset method has been used within this study. Climate scenario data from the Swedish Meteorological and Hydrological Institute, SMHI, typical meteorological years, TMYs, for different locations have been adjusted. There is a large quantity of data for different climate scenarios available from SMHI.

There are many different ways and indicators to express energy performance and moisture performance. Hence, there is a need to use a method where multiple, possibly conflicting goals, expressed in dissimilar units, can be weighted into a single value that accounts for all goals and indicators. This may be solved mathematically by applying Multi Criteria Decision Analysis, MCDA. The general concept of MCDA is firstly to create a value tree with different criteria, which contains different indicators. To transform the indicators into a value (or rating), different methods exist. The standardised ASTM method is based on pairwise comparison of the different indicators relative to each other. E.g. if three different wall assemblies have R-value of 1, 5 and 10, value 5 is five times more desirable over 1, 10 is two times more desirable over 5, etc. Using a value scale, defining different levels of an indicator and a corresponding value, stakeholders may set a level for “not acceptable” where the value of the indicator is zero. This is not possible when the ASTM method is used.

The aggregation, weighting the indicators into a single value, may also be done differently. Commonly, it is done by defining weighting factors for each indicator, describing the relative importance of an indicator to another. The “swing weight method” is based on firstly indentifying the most important indicator, secondly the relatively importance of other indicators in relation to the most important one is defined. By using an evaluation matrix all indicators are pairwise compared and valued. Using the evaluation matrix is more complex but will result in more differentiated weighting factors. The use of environmental indicator systems is a form of MCDA, where the weighting and value of different indicators are already defined.

The objective was to indentify a methodology to evaluate building envelopes, taking into account energy and moisture performance. Based on the literature review, a model for weighting and evaluation of moisture and energy performance was presented. The model does not specify which specific indicators should be used. The reason is that different stakeholders may prefer different indicators. The model uses an evaluation matrix to define the relative importance of the different indicators. The valuation of the different indicators is conducted by allowing stakeholders to define a “not acceptable level” and “excellent” or “best possible outcome”. In between these, two to three additional levels are defined. When the weighted value is aggregated from all the indicators, a performance failure indicator is used. The performance failure indicator is 0 or 1 and is multiplied by the aggregated value. If any indicator is zero, the performance failure indicator is zero; otherwise the value of the performance failure indicator is 1. By using the performance failure indicator, alternatives where one or more indicators are at a non-acceptable level receive an overall value of zero, regardless of the value of the other indicators. The performance failure indicator is thus intended to prevent sub-optimization.

The developed model was tested both for a limited part of a building envelope, but also for a whole building. The tests of the model showed that it is possible to handle a large set of criteria and to weight them into one value. However, the visualisation of the result was rather cluttered.

Future work within this research project will include a historical review of materials and techniques used for building envelopes in the Swedish building stock in order to create a basis for finding and prioritizing common building envelopes. This may be used to investigate different energy renovation measures for the building envelope in the existing building stock.

Furthermore, additional climate scenarios will be studied to create climate files to further investigate possible effects of climate change. The developed model will be used to weight and evaluate the results regarding energy and moisture performance. Using the model, further improvements in usability and regarding how results can be presented will be investigated.

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Articles I

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The importance of a common method and correct calculation of thermal bridges

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KEYWORDS: *Thermal bridges, EN ISO 13789, EN ISO 10211, energy, plus-energy, buildings*

SUMMARY:

This paper elucidates the increased need of correct calculations of thermal bridges for low/near zero energy buildings. The variability of the results from calculations of transmission losses for a building can be large if the calculation method within EN ISO 13789:2007 is not fully understood. A survey has been carried out which shows that there are no consensus in Sweden regarding how to define the transmitting area for a 1-D building component as input for energy calculations and that there is confusion regarding the definition of thermal bridges. It seems that the most common misunderstanding regarding thermal bridges is that the geometrical effect; thermal bridges caused by the fact that they have different internal and external area. Based on the survey different scenarios have been analyzed regarding the impact on a building's energy demand and peak load for space heating. The analysis shows that energy needed for heating and peak load for heating increases by 43% respectively 25% when the worst case scenario is compared with correct calculations. In order to minimize the risk of misunderstanding of areas and thermal bridges should subscripts always be used.

1. Introduction

On the 18th of May 2010, the members of the European Parliament approved the changes to the Energy Performance of Buildings Directive, EPBD (European Parliament, 2010). The recast specifies that by the end of 2020 all new buildings shall be "nearly zero-energy buildings". The nearly zero-energy building is a building with a very high energy performance which means that the energy required should be nearly zero or very low. According to Dokka (2004) the energy design of a nearly zero-energy building should be based on a five step approach:

1. Reduce heat losses
2. Use energy efficient equipment
3. Utilize solar energy
4. Display and control energy consumption
5. Select energy source

To ensure a robust and energy efficient residential building in a Nordic climate, not dependent on complex energy generating installations, the first step is always to reduce the buildings' energy losses. It is therefore important not to underestimate the buildings' heat transmission losses or to evaluate/calculate the heat transmission coefficients in a simplified and incorrect way. Calculation of transmission losses for a whole building or part of a building should follow a standardized calculation method. A common European method is shown in EN ISO 13789 (SIS 2007a).

In design of low energy or near zero energy buildings, a poor estimation of thermal bridges, and thus the space heating demand, could lead to severe economical consequences for the builder, the client and/or the consultants. This paper elucidates the increased need of correct calculations of thermal bridges and presents that the Swedish state of knowledge regarding thermal bridges.

2. Calculation of heat transfer according to the European and International standard EN ISO 13789

The EPBD states that the methodology for calculating the energy performance of buildings should take into account European standards. EN ISO 13790 (SIS, 2008) is a commonly used standard which is also referred to in the national building regulations in most Nordic countries, for example in Norway (KRD, 2010) and Finland (Ympäristöministeriö, 2007). EN ISO 13790 refers to the calculation of transmission and ventilation heat transfer coefficients in EN ISO 13789. In Sweden, there is no standard for calculation the energy performance set in the building regulations, BBR. However, BBR refers to calculations of the average heat transfer coefficient in EN ISO 13789 (Boverket, 2009).

This section focuses on heat transfer according to EN ISO 13789 and the normative standard for thermal bridges in construction, EN ISO 10211 (SIS, 2007b). There are more normative standards which are not in detail studied here. The normative standards are visualised in FIG 1.

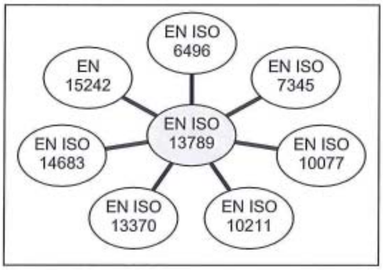

FIG 1. EN ISO 13789 with normative standards

The transmission heat transfer coefficient is calculated according to Equation 1.

$$H_T = H_D + H_g + H_U + H_A \tag{1}$$

Where	H_D	direct heat transfer coefficient (W/K)
	H_g	steady-state ground heat transfer coefficient (W/K)
	H_U	transmission heat transfer coefficient through unconditioned spaces (W/K)
	H_A	transmission heat transfer coefficient to adjacent buildings (W/K)

The direct heat transfer coefficient is calculated according to Equation 2.

$$H_D = \sum_i A_i U_i + \sum_k l_k \Psi_k + \sum_j \chi_j \tag{2}$$

Where	A_i	area of element, i (m^2)
	U_i	thermal transmittance of element, i ($W/m^2 \cdot K$)
	l_k	length of linear thermal bridge (m)
	Ψ_k	linear thermal transmittance of thermal bridge ($W/m \cdot K$)
	χ_j	point thermal transmittance through point thermal bridges (W/K)

To apply the calculation method for direct heat transfer, the building envelope needs to be clearly defined and divided into different elements as shown in FIG 2.

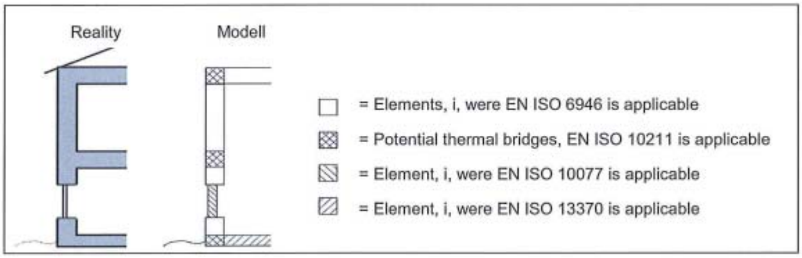

FIG 2. Breakdown of building in different elements and thermal bridges

Measuring of elements can be done according to one of the three methods; internal, overall internal or external dimensions. The differences between the different measuring concepts are visualised shown in FIG 3.

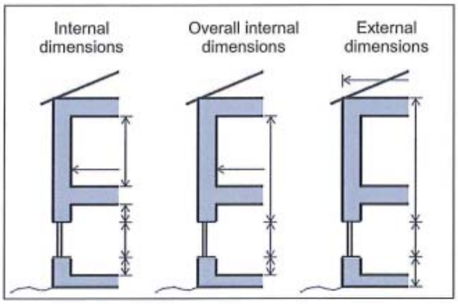

FIG 3. Different types of dimensions according to EN ISO 13789

Calculations to define values for thermal bridges are presented in Equation 3 and Equation 4, where Equation 3 defines linear thermal transmittance and Equation 4 defines point thermal transmittance.

$$\Psi = L_{2D} - \sum_{j=1}^{N_j} U_j \cdot l_j \tag{3}$$

Where	L_{2D}	thermal coupling coefficient obtained from a 2-D calculation (W/m·K)
	U_j	thermal transmittance of 1-D component, j (W/m^2·K)
	l	length over which U_j applies (m)

$$\chi = L_{3D} - \sum_{j=1}^{N_i} U_i \cdot A_i - \sum_{j=1}^{N_j} \Psi_j \cdot l_j \tag{4}$$

Where	L_{3D}	thermal coupling coefficient obtained from a 2-D calculation (W/K)
	U_i	thermal transmittance of 1-D component, i (W/m^2·K)
	A_i	area over which U_i applies (m^2)
	Ψ_j	linear thermal transmittance calculated according to Equation 3 (W/m·K)
	l_j	length over which Ψ_j applies *(m)*

The sum of transmission losses through building elements, the term $\Sigma A_i U_i$, will vary depending on the chosen measuring method. Consequently, the thermal bridges, Ψ-values and χ-values will vary. To clarify which measuring method that will be used to calculate the thermal transmittance of each thermal bridge, the subscripts presented in TABLE 1 will be used:

TABLE 1. Subscripts to clarify used method for measuring

Subscript	Definition
i	Internal
oi	Overall internal
e	External

3. The state of knowledge and application of different methods in Sweden

3.1 The survey

A web based questionnaire was sent out to 100 engineers and architects who had experience from building projects with focus on energy efficiency. The questionnaire was divided into three sections:

- Question 1-4, area concepts:
  Four questions were asked regarding measuring methods used to define different areas in energy calculations and according to BBR
- Question 5-10, assessment of different junctions:
  Six different junctions were presented, as shown in FIG 4, together with the question: Should this junction be regarded as a thermal bridge which increases heat transmission losses in addition to the losses included in building elements?
- Question 11-17, professional background, etc:
  Six different questions regarding professional background, work experience, if they were familiar with energy calculations and calculations to define thermal bridges etc.

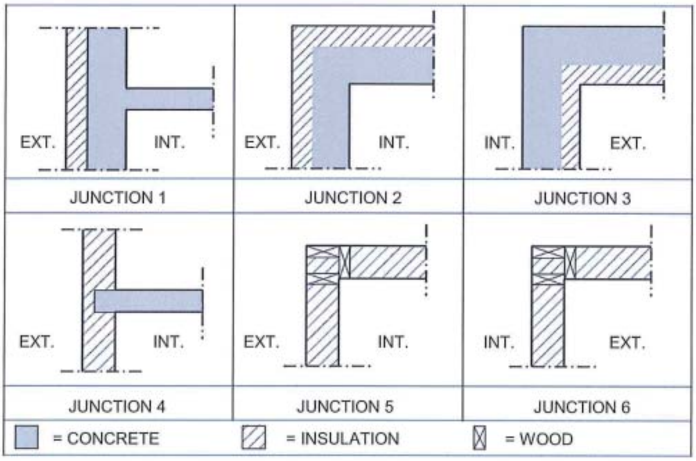

FIG 4. Schematic presentation of junctions, included in the questionnaire. External environment is marked EXT. Internal environment is marked INT.

3.2 Results from the survey

Of the questionnaires sent out; 73 responses were received. Two reminders were sent out. Of the respondents, 84 percent had experience in energy calculations. 53 percent had more than ten years experience. This indicates that most of the respondents have good knowledge of energy calculations.

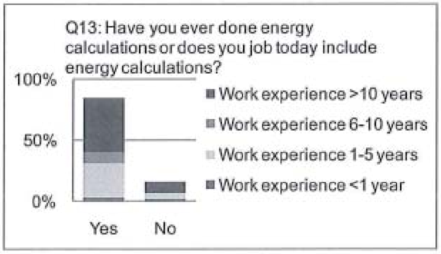

FIG 5. Answers to question 13, sorted on work experience

In the first two questions the respondents were asked how they would measure building elements and a building's enclosing area in order to compile data for energy calculations. The result shows that internal area is most used to measure building elements and external area is most used to define a building's enclosing area. The other measuring options are also used to an extent that exceeds 20 % for each measuring method. In question three and four the respondents were asked how they would interpret the Swedish definitions of A_i and enclosing area, A_{om}, according to BBR:

A_i *Surface area of building element, i, in contact with heated indoor air* (m^2)

A_{om} *Total surface area of the enclosing parts of the building in contact with heated indoor air* (m^2)

The result is more uniform when a definition is given; 57 % respectively 48 % use interior measurement to define A_i and A_{om} according to BBR. Breakdown of the responses is shown in FIG 6.

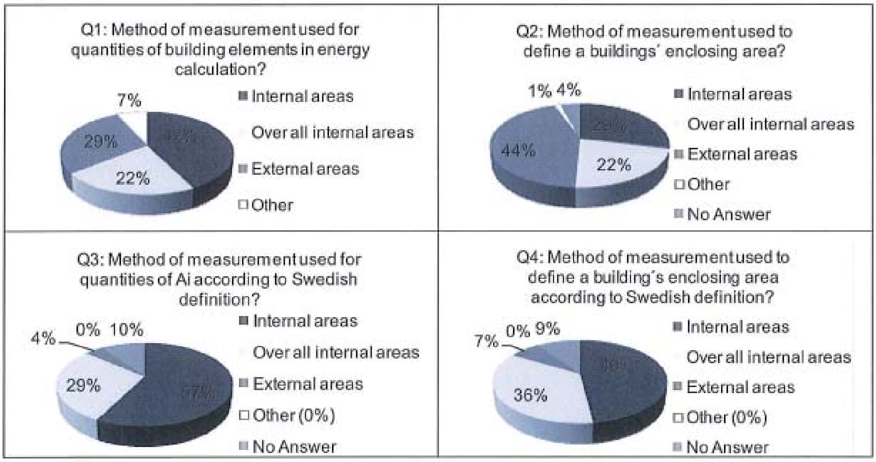

FIG 6. Answers to questions 1-4

As stated in Section 2, the Ψ-values and χ-values will vary depending on the chosen measuring method. In TABLE 2 the effect of the thermal bridges is presented sorted by different measuring methods. The last junction; J6, is a junction were the insulation is penetrated by wood which results in increased thermal transmittance. The effect of the difference between internal and external area is however larger which results in that Ψ_i and Ψ_{oi} should be added into the energy calculations as thermal bridges which decrease the direct heat transfer coefficient.

TABLE 2. The junctions' impact on the thermal heat losses based on choice of measuring method

Junction	Ψ_i	Ψ_{oi}	Ψ_e
Junction 1 – J1	Increase	None	None
Junction 2 – J2	Increase	Increase	Decrease
Junction 3 – J3	Decrease	Decrease	Increase
Junction 4 – J4	Increase	Increase	Increase
Junction 5 – J5	Increase	Increase	Decrease
Junction 6 – J6	Decrease	Decrease	Increase

The answers from question 5-10, assessment of junctions, have been sorted depending on how they choose to measure A_i. The first three junctions (J1-J3), which are thermal bridges due to the effect of difference between internal and external areas shows a large number of errors in the qualitative assessments. The percentage of correct answers for junctions; J1and J2 is 47 and 48 % respectively. In the assessment of J3; 56 percent of the respondents give a correct answer. The junctions J4-J5 are thermal bridges both due to the effect of differences between internal and external area, and by full or partial penetration of the building envelope by materials with a different thermal conductivity. The assessments from the respondents shows a significantly higher correctness when these answers are examined; 88 respectively 89 % of the respondents do a correct assessment. In assessment of junction J6; only 11 % assess the junction correctly.

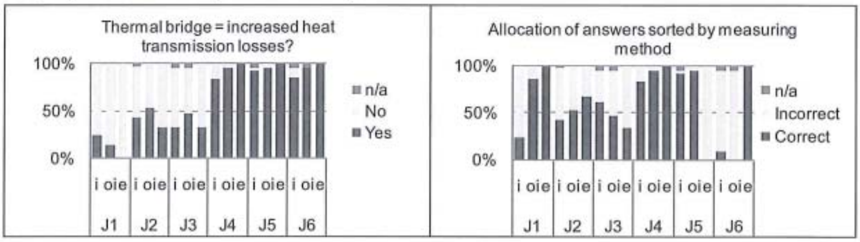

FIG 7. Answers to questions 5-10, sorted by the respondents' choice of measuring method to define A_i

There is little difference in the distribution of correct/incorrect answers based on measurement method.

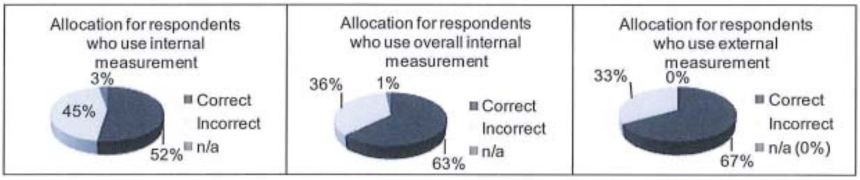

FIG 8. Distribution of correct/incorrect answers to questions 5-10, sorted by the respondents' choice of measuring method to define A_i

The respondents were also asked if they carry out calculations to determine specific values for thermal bridges, 47 % replied yes. Respondents who replied yes were asked to describe the used method. 43 % of the respondents who carry out calculations for thermal bridges use some sort of computer software, the most commonly used software is HEAT (Blocon).

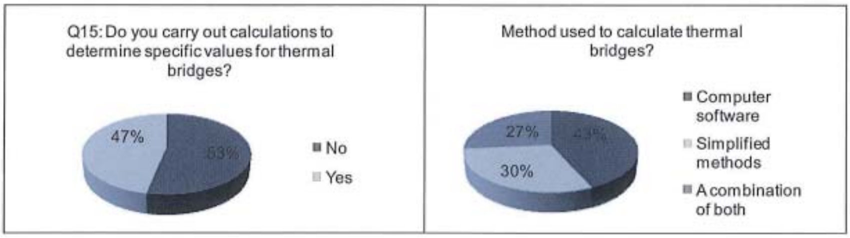

FIG 9. Answers to questions 15, "Do you carry out calculations to determine specific values for thermal bridges?" Respondents who replied yes were asked to describe the used method. The methods have been divided into; computer software, simplified methods and a combination of both.

The most common method to account for thermal bridges today, used by 44 % of the respondents, is to quantify the amount of thermal bridges and apply existing default values for the thermal transmittance. The second most common method, used by 22 percent of the respondents, is to increase thermal transmittance of building components by a certain percentage, i.e. 5-20 % (mean percentage used; 15%).

4. Conclusions

The result from the Swedish survey regarding state of knowledge, interpretation of different measuring methods of a building's dimensions and the assessment of junctions to determine whether they were thermal bridges is not satisfying. The result from the study shows that there is a great difference between which method of measurement the respondents use to quantify building elements and a building's enclosing area. Today, usually several consultants are involved in the design and construction phase of a building. It is possible to imagine a scenario in which the architect will be asked to provide quantities of building components and junctions, the constructor calculates U-values and specific values for thermal bridges and the installation consultant or energy coordinator carries out the actual energy calculation. It seems that the most common misunderstanding regarding thermal bridges is that the geometrical effect of thermal bridges is not understood, in other words; thermal bridges caused by the fact that they have different internal and external area.

We are constantly increasing the use of Building Information Modelling, BIM, in the design and construction of buildings. In order to use models created in BIM-tools as a basis for energy calculations, these tools must be able to distinguish different area definitions.

In order to minimize the risk of misunderstanding of areas and thermal bridges the subscripts, presented in TABLE 1, should always be used. Furthermore, a need has been identified for guidelines how to use the available standards.

5. Acknowledgements

This article is part of the project; Klimatskal 2019, a project funded by The Development Fund of the Swedish Construction Industry and Skanska Sverige AB. The aim is to develop a method to evaluate energy- and moisture performance for building envelops. The authors wish to thank everyone who took the time and answer the questionnaire.

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Articles II

A parametric study of the energy and moisture performance in passive house exterior walls

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Summary

Adding insulation to improve the energy performance of a building with a traditional Swedish wooden construction may increase the risk of mould growth in the wooden construction.
There is a need to address this potential problem since the amount of passive houses and low energy buildings are increasing as a means to reduce energy use, energy dependency and greenhouse gas emissions.
This paper evaluates energy performance and moisture performance simultaneously in order to create a more holistic approach. Space heating demand, peak load for space heating and risk for mould growth are evaluated.
The analysis of these three different aspects shows that there is no contradiction between moisture safety design and energy efficient design. It may however not be suitable to increase the amounts of insulation in traditional wooden constructions without considering risk of mould growth.

Keywords: passive house, energy, moisture, performance, mould, hygrothermal, WUFI, IDA ICE

1. Introduction

Problems with mould growth and high humidity levels in building constructions have been increasing over the last years in Sweden. A Swedish study has shown that many cold attics suffer from high humidity levels and mould growth [1].These problems are already appearing in roof constructions with amounts of insulation which may be considered as standard amounts; 400 mm [2]. The amount of passive houses built in Sweden is increasing [3] and one of the key measures in passive house design is to reduce heat losses [4]. To reduce the heat losses through the building envelope, improved air tightness and reduction of thermal transmittance measures are therefore frequently used in order to achieve a low energy demand for dwellings. To reduce the thermal transmittance more insulation is added to the building envelope or insulation with lower heat conductivity is used. The reduction of thermal transmittance through the building envelope will result in a different microclimate within the building envelope. For example, in a Nordic climate the outer parts of a wall will be colder as the thermal resistance increases, which might give a higher risk for mould growth. Today, the Swedish building regulations, BBR, states that every material used in a building must have a certain maximum moisture level that should not be exceeded during the life cycle of the building. This moisture level is based on the critical moisture level for the actual material including a safety margin. The critical moisture level has to be defined for every material, by the supplier or similar. If it is not defined, 75% relative humidity, RH, should not be exceeded for the material at any time [5]. As 75 % RH is a very strict demand and mould growth is very much dependent not only on RH, but also on temperature and duration [6], there is a need to evaluate the risk for mould growth by considering all of these parameters. This paper discusses energy performance and moisture performance for building envelopes to evaluate the issues of energy use and risk of mould growth together, creating a more holistic approach.

2. Methods

2.1 Description of case study

The case study is based on a terraced house with three dwellings in the southwestern parts of Sweden Göteborg. Characteristics of the building are presented in Table 1 and Fig 1.

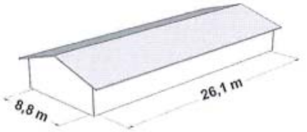

Fig. 1 Case study

Table 1 Characteristics of reference building (measuring is based on internal dimensions)

Characteristic	Data	Unit
Heated area	229.7	m^2
Window and door area	40.9	m^2

It is assumed that the building is designed with constructions which have a thermal transmittance suitable for passive houses. The exterior walls are constructed with standard amounts of insulation but the builder whishes to investigate the effect of increased amounts of insulation.

2.2 Simulations

Simulations are conducted to:

- Evaluate if there is a remarkable increased risk of mould growth on wood in an exterior wall with low thermal transmittance compared to an exterior wall with thermal transmittance considered as standard
- Evaluate the different constructions' effect on the space heating demand and peak load for heating

Taking the step from an outer exterior wall construction with standard amounts of insulation (U_c=0.17 W/m^2K) to an exterior wall with low thermal transmittance (U_c=0.09 W/m^2K), that is suitable for a passive house, is done comparing two different approaches:

- Traditional approach; the thermal transmittance is decreased by increasing the amount of insulation to the construction on the inner side of the load bearing structure, w1 in Fig. 2. Exterior insulation, w2, is kept to 0 mm. The benefit of this approach is that the carpenters relatively fast can achieve a wind protected and, fairly increased, thermal indoor environment which creates a better working environment for the carpenters
- Decreasing thermal bridges and keeping the wooden structure warm. This approach firstly focuses on decreasing the thermal transmittance by adding insulation to the outer side of the load bearing structure, to a maximum of 70 mm, w2 in Fig 2, before more insulation is added to the inner side of the load bearing construction, w1

All other constructions are kept constant. A summary of constructions used in the simulations is presented in Table 2 and Table 3.

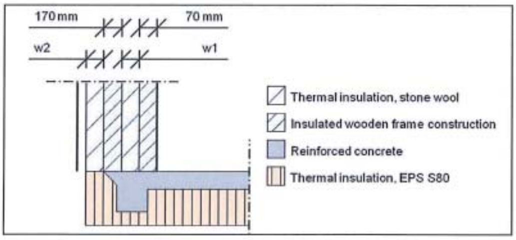

Fig. 2 Sketch of exterior wall and ground construction

Table 2 Constructions for the building envelope used in all simulations and calculations

Construction	Description
Roof	Wooden roof truss with 620 mm of loose stone-wool insulation. U=0.07 W/m^{2}K
Slab on ground	Concrete slab on ground, insulated with 350 mm EPS S80. U=0.08 W/m^{2}K
Windows	Triple glazed window, LE-coatings + Argon filling. U_w=0.90 W/m^{2}K
Window doors	Triple glazed window, LE-coatings + Argon filling. U_w=0.90 W/m^{2}K
External doors	U = 1.0 W/m^{2}K

Table 3 External walls in different cases (references to w1 and w2 are according to Fig 2)

Case	Description		
Base line	w1 = 0 mm	w2 = 0 mm	U=0.17 W/m^{2}K
Scenario 1.1 traditional approach	w1 = 70 mm	w2 = 0 mm	U=0.13 W/m^{2}K
Scenario 1.2 minimizing thermal bridges	w1 = 0 mm	w2 = 70 mm	U=0.13 W/m^{2}K
Scenario 2.1 traditional approach	w1 = 220 mm	w2 = 0 mm	U=0.09 W/m^{2}K
Scenario 2.2 minimizing thermal bridges	w1 = 145 mm	w2 = 70 mm	U=0.09 W/m^{2}K

2.2.1 Hygrothermal simulations

Hygrothermal simulations are conducted using the numerical software WUFI 1D Pro [7]. A summary of the boundary conditions and input data used in the hygrothermal calculations are shown in Table 4.

Table 4 Boundary conditions and input data for WUFI Pro 1D 5.0

Data	Value
Time span	3 years
Cloud cover	0.66
Cardinal direction	South facade
Ventilation of air gap	50 h^{-1}
Initial RH, all materials	80 %
Outdoor temperatur, Göteborg (mean, min, max)	8.8°C, -12.2°C, 27.8°C
Outdoor relative humidity, Göteborg (mean, min, max)	74%, 19%, 94%
Fraction of driving rain leakage	1%
Indoor climate	According to equation 1 and equation 2

$$T_i = \begin{cases} 20, T_{outdoor} \leq 10 \\ 15 + 0.5T_{outdoor}, 10 < T_{outdoor} < 20 \\ 25, T_{outdoor} \geq 20 \end{cases} \tag{1}$$

Where

T_i Indoor temperature

$T_{outdoor}$ Outdoor temperature

$$RH_i = \begin{cases} 30, T_{outdoor} \leq -10 \\ 40 + T_{outdoor}, -10 < T_{outdoor} < 20 \\ 60, T_{outdoor} \geq 20 \end{cases} \tag{2}$$

Where
RH_i Relative humidity in indoor air

2.2.2 Energy simulations

Calculations of thermal transmittance for constructions and thermal bridges follow EN ISO 6946 [8], EN ISO 13370 [9] and EN ISO 10211 [10] calculated with HEAT 3D 5.1 [11]. IDA ICE 4.1 [12] is used to simulate the annual energy demand for space heating and peak load for heating. A summary of the boundary conditions and input data used in the energy simulations are shown in Table 5. Input data for materials in the HEAT calculations are summarised in Table 6.

Table 5 Boundary conditions and input data for IDA ICE 4.0

Data	Value
Climate data	Göteborg 1977
Indoor temperature	21 °C
Ventilation	0,35 l/s, m^2 heated floor area
Temperature efficiency of heat exchanger	80 %
Internal heat gains	4 W/m^2 heated floor area

Table 6 Boundary conditions and input data for HEAT 3D 5.1

Material	Design thermal conductivity [W/mK]
Mineral wool	0.037
Wood	0.13
Gypsum board	0.25
Insulation under floor slab	0.038
Insulation under footing	0.033
Contrete 1 % reinforcement	2.3
Ground soil	2.0
Flooring	0.18

2.3 Evaluation of the results – the m-model

To quantify the results of the simulations, energy needed for heating, peak load for heating and risk of mould growth are analysed. Energy needed for heating and peak load for heating are extracted from IDA ICE 4.0. To analyse the risk for mould growth relative humidity and temperature at the interior side of the wind barrier are extracted from WUFI Pro 1D and analysed. This specific section of the wall is chosen due to that it has direct contact to the load bearing wood studs and it is predicted that the highest risk of mould growth is in this section. The analysis is carried out using a model which makes it possible to evaluate the risk for mould growth on wood called the m-model. The following part of this section gives an overview of the theory behind the m-model. A more complete and extensive description of the m-model is given in [13].

The m-model uses critical moisture levels that follow the directions in [14] and [15]. In all, a total of six critical moisture durations are used, presented in Fig 3.

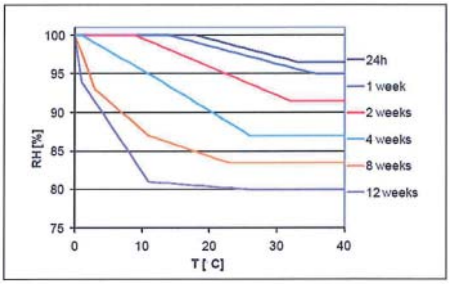

Fig. 3 Six critical moisture levels, data from Nilsson [14] and Viitanen [15]. Six durations, or critical risk times, are used: 24 h, 1 week, 2 weeks, 4 weeks, 8 weeks and 12 weeks. Figure from [13]

A parameter, called m, is calculated based on relative humidity, temperature and duration as shown in Equation 3.

$$m = \frac{RH_{act}(t)}{RH_{crit}(T(t))\gamma} \tag{3}$$

where

$RH_{act}(t)$	The actual relative humidity in the material, at time t [h]
$RH_{crit}(T(t))$	The critical relative humidity at temperature T and time t [h], based on the relations in Fig 3. There is a mathematical relation between temperature and RH_{crit} for every critical duration, i.e. six mathematical expressions of RH_{crit}.
γ	Safety factor that is used when implementing the m-model, for example in moisture safety design. In this analysis is the factor set to 0.97.

$m \geq 1$ implies that the actual conditions have exceeded the critical levels during one time step. For each time step *m* is calculated for each of the six critical durations as shown in Fig 3. All time steps where $m \geq 1$ are summarized separately for each duration, and constitutes the accumulated risk time. The m-model also handles dehydration, which means that it does not add two separate periods where $m > 1$ without dealing with the dehydration that occurs in between. The accumulated risk time for each duration curve is divided with the critical risk time. The quota is called critical duration quota, CDQ. If CDQ≥1.0, mould will in theory be initiated.

3. Results

Two examples of relative temperature distribution are shown in Fig 4. The relative temperature distribution is close to equal, comparing the two different approaches; step 1.1 and step 1.2. However, it is possible to see that the wooden studs (light yellow in the schematic descriptions) in step 1.2, which are given an external insulation, have a relatively warmer micro climate.

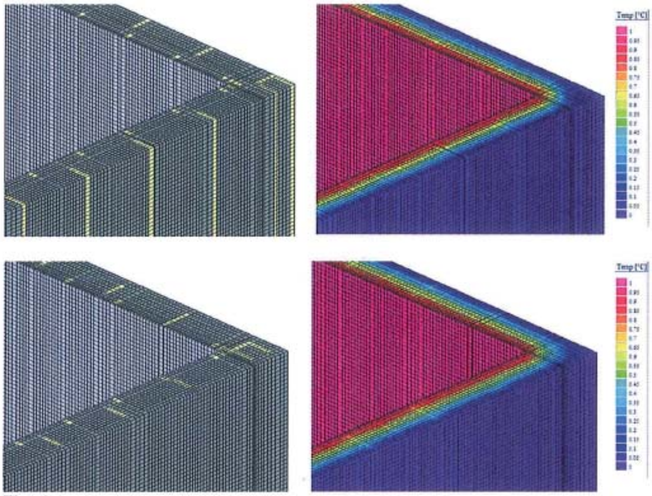

Fig. 4
Top left; schematic description of external wall corner: Scenario 1.1
Top right; relative temperature description of external wall corner: Scenario 1.1
Bottom left; schematic description of external wall corner: Scenario 1.2
Bottom right; relative temperature description of external wall corner: Scenario 1.2

Thermal bridges for the different steps are presented in Table 7. The vast majority of the thermal bridges decrease as more insulation is used, but not all. This is mainly due to geometrical effects. For example; more insulation results in larger window bays which increase the transmitting area. Adding insulation to the outer side of the wooden frame construction results in lower peak load for space heating and energy needed for space heating compared to the traditional approach of adding insulation on the inner side, which can be seen in Fig 5.

Table 7 Linear thermal transmittance

Junction	Linear thermal transmittance Ψ_l [W/mK]				
	Base case	Scenario 1.1	Scenario 1.2	Scenario 2.1	Scenario 2.2
External wall – internal load bearing wall	0.059	0.043	0.042	0.026	0.026
External wall – interior non load bearing wall	0.017	0.013	0.013	0.009	0.009
External wall corner	0.058	0.035	0.045	0.027	0.028
External wall – window/door	0.026	0.031	0.019	0.043	0.030
External wall – roof construction (long sides)	0.048	0.038	0.040	0.031	0.030
External wall – roof construction (gables)	0.053	0.041	0.041	0.033	0.032
External wall – ground slab	0.220	0.191	0.159	0.202	0.174

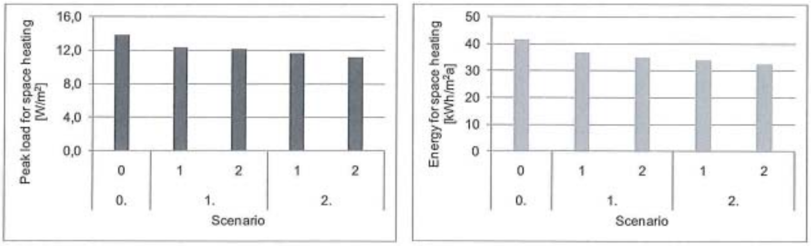

Fig. 5 Results from the IDA ICE simulations. Left; Peak load for space heating. Right; annual energy needed for space heating

The maximum CDQ is presented in Fig 6. The analysis shows that adding insulation in moderate quantities using the traditional approach (Scenario 1.1) and reaching a U-value of 0.13 W/m^{2}K, will not result into CDQ>1. If more insulation is added in the traditional way (Scenario 2.1), mould growth will theoretically be initiated. By applying the simple measure of adding insulation to the outer side of the wooden frame construction results in a slightly lower CDQ in Scenario 1.2 and a low increase of CDQ in Scenario 2.2. Choosing the approach of minimizing thermal bridges will result into a more energy efficient and moisture safe design see Fig 7.

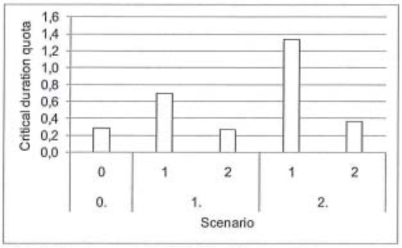

Fig. 6 Maximum critical duration quota

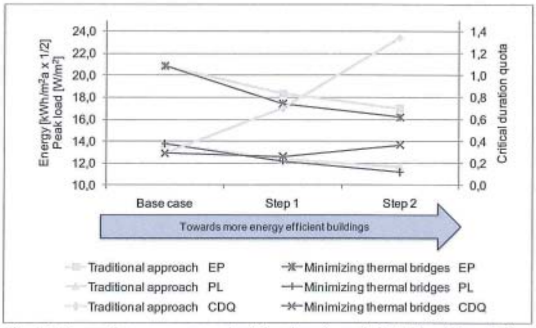

Fig. 7 Annual energy needed for heating (EP), Peak load for heating (PL) and Critical duration quota (CDQ) displayed simultaneously. Note: to get the annual energy demand, the value given in the y-axis should be multiplied with 2

4. Discussion and conclusions

The analysis of these three different factors shows that there is no contradiction between moisture safety design and energy efficient design. It may however not be suitable to increase the amounts of insulation in traditional wooden constructions without considering a risk of mould growth.
It is obvious that increased amounts of insulation will lead to a colder micro climate in exterior parts of building envelopes. However, it does not have to be considered as a great risk if appropriate measures are applied. Insulation, or other materials, added to the exterior side of a wooden frame construction must have a critical moisture level which exceeds wood.

It is important to point out that this analysis has been carried under a specific set of boundary conditions. For example a wall facing south was chosen which, in the Göteborg climate, is the cardinal direction most afflicted by driving rain. Changing the boundary conditions such as cardinal direction, fraction of driving rain leakage etc. will of course change the results. In other words, this study does not claim to show that a certain construction will suffer from mould growth or not. It does however show that, by applying simple measures, it is possible to substantially reduce the risks.

5. Acknowledgements

This paper is part of the project; Klimatskal (building envelope) 2019, a project funded by The Development Fund of the Swedish Construction Industry and Skanska Sverige AB. The purpose of the project is to develop a method to evaluate energy- and moisture performance for building envelopes.

The authors wish to thank Peter Brander, Åse Togerö and Bengt Bengtsson at Skanska Sverige AB for providing the m-model and also for help and support regarding hygrothermal simulations in WUFI and feedback during the writing.

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Articles III

Thermal bridges in passive houses and nearly zero-energy buildings

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Summary

An important strategy for climate mitigation is reduction of energy use in buildings. One approach is to build or renovate buildings applying passive house design or a zero-energy building approach. The first step towards passive house design is reduction of heat losses, and therefore improving the thermal resistance of the building envelope. This is reached by adding more insulation and/or insulation with low thermal conductivity. A recent study shows that professionals unfortunately are not always aware of the concept of thermal bridges combined with different definitions of measuring of building elements. Furthermore, the effect of thermal bridges is usually taken into account using simplified methods which may not be correct. This paper explains the differences in different measuring methods which may be applied today according to European standards, and the possible impact on the specific values of linear thermal bridges. The results show that the relative effect of thermal bridges may increase when the thermal resistance of the building envelope is improved. It also shows that the difference between simplified calculations and more accurate calculations increases when the thermal resistance of the building envelope is improved. The case study shows that the effect of misunderstandings or carelessly handling of thermal bridges in the design phase may lead to an underestimation of peak power for space heating and energy demand for heating by 29 % and 37% respectively. To minimize the risk for undersized heating systems and increased space heating demand, subscripts indicating the applied measuring method (used in calculations to determine specific values of thermal bridges) should always be used when thermal bridges are presented.

Keywords: passive house, thermal bridges, energy, EN ISO 13789, EN ISO 10211

1. Introduction

Buildings today account for 40% of the world's primary energy use and 24% of the greenhouse gas emissions [1]. The building sector is expanding. Therefore, reduction of energy consumption and the use of energy from renewable sources in the buildings sector constitute important measures required to reduce energy dependency and greenhouse gas emissions.

The share of dwellings constructed as low energy buildings and passive houses has increased markedly in the recent years in Sweden. The proportion of dwellings built as low energy buildings has increased from 0.7% in 2008 to 7.2% in 2010. If one considers only the segment of multi dwelling buildings the share is even higher; 11.2 % in 2010 [2]. In the recast of the Energy Performance of Buildings Directive, EPBD, the European parliament has stated that by the end of 2020 all new buildings shall be "nearly zero-energy buildings" [3]. The nearly zero-energy building is defined as a building with a very high energy performance, which means that the energy required should be nearly zero or very low.

A common concept to design and build an energy efficient building is to apply the Passive House design principle. The first step in the Passive House design principle is to reduce heat losses by constructing a well insulated and air tight building envelope in combination with balanced ventilation with high system heat recovery efficiency [4].

When a building is designed according to these principles, the major part of the energy needed for space heating will be related to thermal transmission through building elements and thermal bridges. Poor calculation of thermal bridges may therefore lead to an increased space heating demand and poor indoor climate. Further, this may lead to economical consequences for the builder, the client and/or the consultants. It may also lead to decreased credibility for energy efficient buildings if the calculated/simulated energy performance does no correlate with the measured energy performance. It may also lead to reduced thermal comfort in the building.

A Swedish study based on a questionnaire has been carried out which shows that the definitions of a thermal bridge is not fully understood and that even professionals are not always fully aware of the implications of the different methods used to calculate transmission losses [5]. The study also indicates that the calculations to determine the size of thermal bridges today often are done with simplified mathematical methods, which usually are 1-D, or by increasing the thermal transmittance of building elements by a certain percentage factor. To exemplify the impact and to elucidate the increased need of correct calculations of thermal bridges for passive houses and nearly zero-energy buildings comparative calculations have been carried out for two junctions where the thermal bridges are calculated using 1-D and 2-D analysis. Furthermore, a case study has been carried out where the annual space heating demand, peak load for heating and the needed supply air temperature (if the building is to be heated by pre heated supply air) have been calculated for a building designed as a passive house in Sweden. These analyses are based on different scenarios regarding consideration of thermal bridges.

2. Method

2.1 Theoretical background – Calculation of heat transfer through building elements and thermal bridges

This section focuses on heat transfer according to EN ISO 13789 [6] and thermal bridges according to EN ISO 10211 [7].

In order to calculate heat transmission through a building envelope there is a need to calculate a heat transfer coefficient according to Equation 1.

$$H_D = \sum_i A_i U_i + \sum_k l_k \Psi_k + \sum_j \chi_j \qquad (1)$$

Where A_i area of element, i (m^2)
U_i thermal transmittance of element, i ($W/m^2 \cdot K$)
l_k length of linear thermal bridge (m)
Ψ_k linear thermal transmittance of thermal bridge ($W/m \cdot K$)
χ_j point thermal transmittance through point thermal bridges (W/K)

Calculations for thermal bridges are presented in Equation 2 and Equation 3, where Equation 2 defines linear thermal transmittance and Equation 3 defines point thermal transmittance.

$$\Psi = L_{2D} - \sum_{j=1}^{N_j} U_j \cdot l_j \qquad (2)$$

Where L_{2D} thermal coupling coefficient obtained from a 2-D calculation ($W/m \cdot K$)
U_j thermal transmittance of 1-D component, *j* ($W/m^2 \cdot K$)
l length over which U_j applies (m)

$$\chi = L_{3D} - \sum_{j=1}^{N_j} U_i \cdot A_i - \sum_{j=1}^{N_j} \Psi_j \cdot l_j \qquad (3)$$

Where L_{3D} thermal coupling coefficient obtained from a 2-D calculation (W/K)
U_i thermal transmittance of 1-D component, *i* (W/m^2·K)
A_i area over which U_i applies (m^2)
Ψ_j linear thermal transmittance calculated according to Equation 3 (W/m·K)
l_j length over which Ψ_j applies (m)

Measuring of lengths and areas for Equation 1, Equation 2 and Equation 3 can be done according to one of the three methods; internal, overall internal or external dimensions. The differences between the different measuring concepts are visualised in Fig. 1.

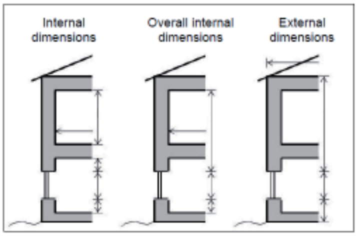


Fig. 1 Different types of dimensions according to EN ISO 13789

The sum of heat transmission through building elements, the term $\Sigma A_i U_i$, will vary depending on the measuring method chosen. Also the specific values for thermal bridges, Ψ-values and χ-values, will vary. To avoid misunderstandings the subscripts in Table 1, showing the used measuring method, will be used when thermal bridges are presented.

Table 1 Subscripts to clarify used method for measuring

Subscript	Definition
i	Internal
oi	Overall internal
e	External

2.2 Calculations and simulations

Calculations to determine thermal transmittance, for building elements and thermal bridges, are carried out using HEAT 2D 7.1 [8]. The effective thermal conductivity, λ', for quasi-homogeneous layers is calculated according to Equation 4.

$$\lambda' = \frac{d}{\dfrac{A}{L_{3D}} - R_{si} - R_{se} - \sum \dfrac{d_j}{\lambda_j}} \qquad (4)$$

Where d thickness of the thermal inhomogeneous layer (m)
A area of building component (m^2)
L_{3D} thermal coupling coefficient of building component (W/K)
d_j thickness of any homogeneous layer in the building component (m)
λ_j thermal conductivity of homogeneous layer (W/m·K)

The simplified method, 1-D analysis, is shown in Equation 5.

$$\Psi_{1D} = U_{th} \cdot l_{th} \qquad (5)$$

Where U_{th}	thermal transmittance of 1-D component, *th*, with reduced heat resistance (W/m^{2}K)
l_{th}	length over which U_{th} applies (m)

To simulate the annual energy use for heating IDA ICE 4.1 [9] is used. The peak load for heating is calculated according to the Swedish criteria for passive houses [10]. The supply air temperature, if preheated supply air is used for space heating, is calculated according to Equation 6.

$$T_{\text{supply}} = \frac{P}{q \cdot \rho \cdot c_p} + \left(T_{\text{outdoor}} + \eta \cdot \left(T_{\text{indoor}} - T_{\text{outdoor}}\right)\right) \qquad (6)$$

Where P	peak load for space heating (W)
q	ventilation air flow (l/s)
ρ	density of air (kg/m^3)
c_p	heat capacity of air (J/kg, K)
η	efficiency of heat exchanger in ventilation unit (%)
$T_{outdoor}$	Design outdoor temperature at the specific location (°C)
T_{indoor}	Design indoor temperature (°C)

2.2.1 Differences in calculated thermal transmittance through thermal bridges based on 1-D and 2-D analysis

In the first example comparative calculations are carried out for two junctions, Junction 1 and Junction 2 (J1 & J2). The thermal bridges calculated using 1-D and 2-D analysis are shown in Fig 2. J1 represents a light-weight infill wall connected to an intermediate concrete floor. The slab edge, a thermal bridge, is insulated with 100 mm of mineral wool. J2 represents a window connected to a precast concrete sandwich wall. To be able to mount the window; the inner concrete construction is thickened into the window bays. To reduce the thermal bridge, the end of the thickened section is insulated with 30 mm of mineral wool. In J1, w1 is varied from 100 to 400 mm which results in U-values from 0.24 to 0.10 W/m²K. In J2, w2 is varied from 90 to 320 mm which results in U-values from 0.26 to 0.09 W/m²K. Note that the amount of insulation over the thermal bridge is not varied. Input data for the analysis is presented in Table 3.

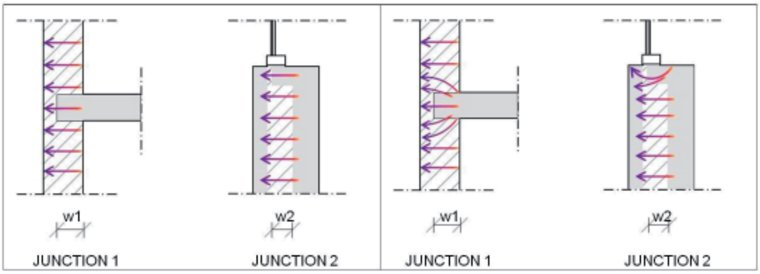
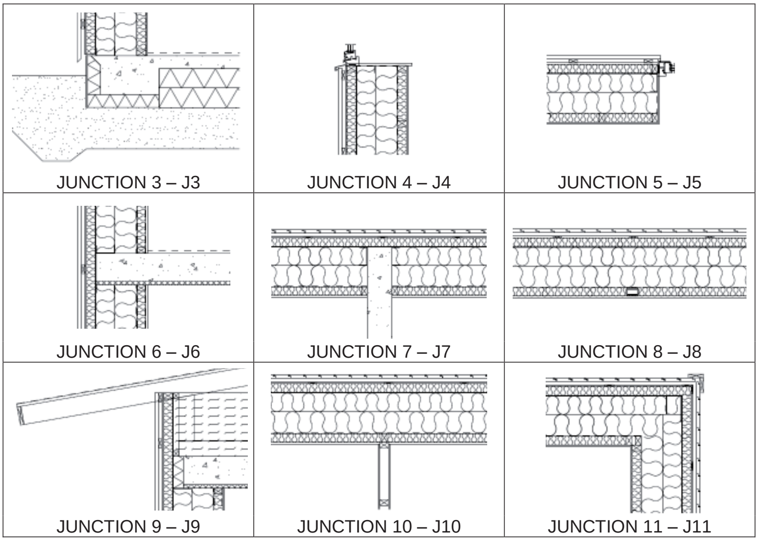


Fig. 2 Schematic presentation of junctions; J1 and J2 In the figures to the left an incorrect assumption, 1-D heat flow, is visualised, in the figures to the right a 2-D heat flow is visualised. The grey area represents concrete, the hatched area the insulated section.

2.2.2 Differences in calculated thermal transmittance through thermal bridges based on different measuring methods

As already explained in the theoretical background, the calculated thermal transmittance of a thermal bridge may differ due to the chosen measuring method. In Fig 3 nine different possible thermal bridges are presented. Linear thermal transmittances for the junctions are calculated based on all three measuring methods. Input data for the analysis is presented in Table 3.



JUNCTION 3 – J3 JUNCTION 4 – J4 JUNCTION 5 – J5
JUNCTION 6 – J6 JUNCTION 7 – J7 JUNCTION 8 – J8
JUNCTION 9 – J9 JUNCTION 10 – J10 JUNCTION 11 – J11

Fig. 3 Schematic presentation of junctions; J3-J11
J3: non load bearing infill wall mounted on a ground floor slab
J4: window connection to a non load bearing infill wall with marble window sill
J5: window connection to a non load bearing infill wall with gypsum window bay
J6: non load bearing infill wall connected to an intermediate floor
J7: non load bearing infill wall connected to a load bearing intermediate wall
J8: load bearing steel pillar inside the a non load bearing infill wall
J9: non load bearing infill wall connected to an attic floor
J10: non load bearing infill wall connected to non load bearing intermediate wall
J11: external wall corner

2.2.3 Possible differences in energy needed for space heating

The junctions presented in Fig 3 are used in a fictive terraced house, designed as a passive house in Sweden. The building contains four dwellings with a varying heated area; 118-130 m^2. The characteristics of the building are presented in Fig 4 and Table 2. The annual energy use for heating, peak load for heating and the needed supply air temperature (if the building is to be heated by pre heated supply air) have been calculated for five different scenarios:

- Scenario 1
  External measuring used to determine A_i, no thermal bridges added
- Scenario 2
  Over all internal measuring used to determine A_i, thermal bridges considered by increasing thermal transmittance by 15 percent
- Scenario 3

Internal measuring used to determine A_i, thermal bridges considered by increasing thermal transmittance by 15 percent

- Scenario 4
  Internal measuring used to determine A_i, thermal bridges added by applying values for Ψ_e
- Scenario 5
  Internal measuring used to determine A_i, thermal bridges added by applying values for Ψ_i

In the scenarios described above, scenario 5 is correct and all other scenarios examples of possible misunderstandings.

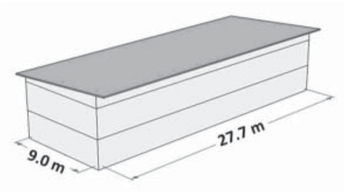


Fig. 4 Reference building

Table 2 Characteristics of reference building (measuring is based on internal dimensions)

Characteristic	Data	Unit
Heated area	498.0	m^2
Window and door area	72.5	m^2
Quantity of J3	73.4	m
Quantity of J4	52.6	m
Quantity of J5	157.8	m
Quantity of J6	73.4	m
Quantity of J7	40.0	m
Quantity of J8	80.6	m
Quantity of J9	73.4	m
Quantity of J10	110.1	m
Quantity of J11	20.0	m

Table 3 Input data for calculations in HEAT 2D 7.1 and IDA ICE 4.1

	Input data	Unit	Comments
Climate data	Göteborg		Latitude 58°N
Indoor temperature	21	°C	-
Design outdoor temperature	-15	°C	-
Air permeability	0.5	h^{-1}	At 50 Pa, EN 13829
Ventilation	0.35	l/s, m^2	m^2, heated area
η, ventilation heat exchanger	80	%	-
Internal heat gains	4	W/m^2	From people and electrical equipment
Ground	$\lambda = 2.0$	W/mK	According to EN ISO 13370
Concrete	$\lambda' = 2.3$	W/mK	Concrete 1% steel reinforcement
Insulation under floor slab	$\lambda = 0.038$	W/mK	EPS S80
Insulation under footing	$\lambda = 0.033$	W/mK	EPS S400
Mineral wool	$\lambda = 0.037$	W/mK	Standard mineral wool
Insulated layer in J1	$\lambda' = 0.050$	W/mK	Insulated wood frame construction
Insulated layer in J2	$\lambda' = 0.033$	W/mK	EPS C80 + reinforcement ladders
Outer part of walls J3-J8	$\lambda' = 0.034$	W/mK	High density mineral wool
Insulated stud section1 J3-J8	$\lambda' = 0.072$	W/mK	Insulation + slotted steel studs
Insulated stud section2 J3-J8	$\lambda' = 0.050$	W/mK	Insulated wood frame construction
Floors	$\lambda = 0.24$	W/mK	Equal to high density plywood
Steel	$\lambda = 50.0$	W/mK	According to EN ISO 10456
Gypsum board	$\lambda = 0.25$	W/mK	According to EN ISO 10456
Marble window sill	$\lambda = 3.50$	W/mK	According to EN ISO 10456
Fixed triple glazed window	$U_w = 0.90$	W/m^{2}K	LE-coatings + Argon filling
Surface resistance	$R_{si} = 0.13$	m^{2}K/W	Used in all calculations
Surface resistance	$R_{se} = 0.04$	m^{2}K/W	Used in all calculations

3. Differences in calculated thermal transmittance when applying different analysis measuring methods

3.1 Differences in calculated thermal transmittance through thermal bridges based on 1-D and 2-D analysis

The comparison shows that the specific thermal transmittance decreases slightly with the increased wall thickness if a 1-D analysis is carried out. This is due to that the thermal resistance increases slightly due to increased amount of concrete at the part of the section were the thermal bridge occurs. The amount of insulation, 100 and 30 mm respectively, is the same. If a proper 2-D analysis is carried out, the specific linear thermal transmittance for the thermal bridge will increase as the heat resistance for the wall increases. This is due to the effect of 2-D heat flow.

Results from calculations and the relative difference (%) between simplified (1-D) and 2-D analysis are presented in Fig 5. The analysis shows that the difference between simplified (1-D) calculations and 2-D-analysis may be as much as 40% if the external wall is well insulated.

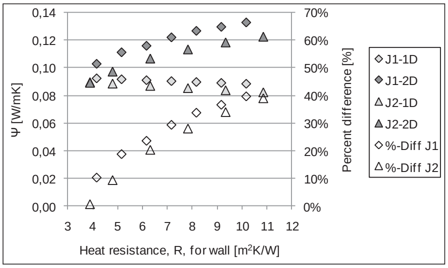


Fig. 5 Results from simplified (1-D) and 2-D-analysis of junctions; J1 and J2

A comparison is also made regarding how much the U-value should be increased to account for the thermal bridge. In the comparison, it is assumed that the relationship between quantities of junctions (m) and wall (m^2) is 1/3. The result is shown in Fig 6. The analysis shows that for a moderately insulated wall, U = 0.2 W/m^2K, the effect of the thermal bridges may result in an increase of U-value by ~15%. The increase of the U-value for a well insulated wall may be >40%.

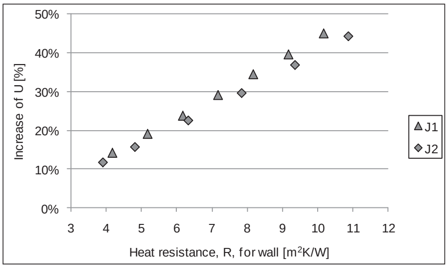


Fig. 6 Increase of U-value when considering the effect of thermal bridges

3.2 Differences in calculated thermal transmittance through thermal bridges based on different measuring methods

The results from the calculations of thermal bridges are shown in Table 4. The junctions where thermal bridges mainly are caused due to partial penetration of the building envelope by material with a different thermal conductivity (J3, J6 and J7), the percentage difference between Ψ_i and Ψ_e is 15-21%. The junctions who show the greatest difference (J10 and J11) between Ψ_i and Ψ_e are junctions with a large difference between internal and external area.

Table 4 Results from analysis of thermal bridges

Junction	Ψ_i [W/mK]	Ψ_{oi} [W/mK]	Ψ_e [W/mK]	Percentage difference between Ψ_i and Ψ_e [%]
J3	0.325	0.325	0.263	21%
J4	0.035	0.035	0.035	0%
J5	0.033	0.033	0.033	0%
J6	0.161	0.135	0.135	18%
J7	0.139	0.120	0.120	15%
J8	0.002	0.002	0.002	0%
J9	0.141	0.141	0.022	146%
J10	0.009	<0.000	<0.000	195%
J11	0.024	0.024	-0.068	422%

3.3 Possible differences in energy needed for space heating, peak load and supply air temperature

The analysis shows that the thermal bridges account for 28 % of the transmission losses when the transmission heat transfer coefficient, H_T, is calculated in scenario 5. This can be compared to the transmission losses due to doors, windows and window doors which accounts for 31 % of the transmission losses. The difference between scenario 1 and scenario 5 is an increase of H_T by 23 % and increased supply air temperature by 11 °C. If an indoor temperature of 21 °C is requested at the design outdoor temperature there will be a need to preheat the supply air to 48°C. See Fig 7 for H_T and needed supply air temperature for all scenarios.

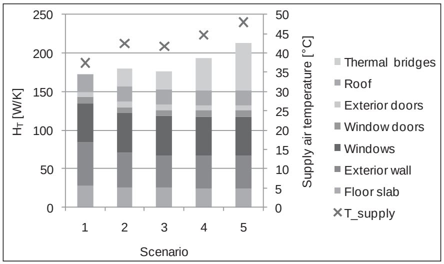


Fig. 7 Transmission heat coefficient, H_T, and required supply air temperature if preheated air is used for space heating, based on different scenarios

As can be seen in Fig 8; the energy demand for space heating varies between 19 and 30 kWh/m^{2}a for the different scenarios and the peak load for space heating varies between 10 and 14 W/m^2. In other words, the underestimation of energy demand for space heating and peak load for heating in scenario 1 compared to scenario 5 is 37% and 29% respectively.

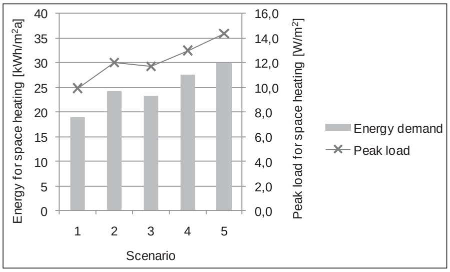


Fig. 8 Annual energy demand, for space heating and peak load for space heating based on different scenarios

4. Discussion and conclusions

The difference between specific values and impact of thermal bridges may be large when comparing thermal bridges based on internal measuring and external measuring. This paper shows that it is not suitable to consider the effect of thermal bridges by increasing the calculated thermal transmission losses due to building elements, the term $\Sigma A_i U_i$, by a fixed percentage or by using default values for specific linear transmittance. It is not suitable due to that:

- The impact of thermal bridges increases when the thermal resistance of the building envelope increases
- The specific values may increase (as shown in Fig 5)

The analysis also elucidates the need for clear communication between consultants in the design phase of a building project. If an architect and a HVAC engineer should collaborate to compile the needed basis for the energy design of a passive house, including energy simulations and the design of the heating system, there may be a risk of misunderstanding leading to:

- Increased annual energy need for space heating
- Undersized heating systems
- High supply air temperature needed (if preheated air is used for space heating)
- Reduced thermal comfort

To minimize this risk of misunderstanding, the subscripts presented in Table 1 should always be used when calculated values for thermal bridges are presented. Correct calculations and communication, with subscripts, should reduce the risk of misunderstandings and performance failure of passive houses and nearly zero-energy houses.

In this study was internal measuring of building elements in combination with Ψ_i used as the correct approach. It is of course possible to apply both external measuring or over all internal measuring to quantify building elements as long as the correct values for thermal bridges are considered in these cases (Ψ_e for external measuring and Ψ_{oi} for over all internal measuring)

In the Swedish building regulations, BBR [11], there are today no references to which measuring method that should be used when quantities of A_i are defined. They do, however, set requirements for maximum allowed average heat transfer coefficient, which is equal to H_T divided by the total surface area of the enclosing parts of the building. This requirement in combination with the lack of clear guidelines regarding which measuring method that should be used makes it possible for unscrupulous builders to interpret the regulations in the way most suitable for them.

In this specific reference building, nine potential thermal bridges were investigated which were considered to be the most relevant in this case. In Sweden, a variety of building systems are used and the thermal transmittance due to thermal bridges varies between different building systems and due to different construction solutions for junctions within the different building systems. This study should therefore not be used as a basis to draw conclusions regarding how much of a building's transmission losses that occur through thermal bridges, but more as an example of how large errors that may occur if you do not understand and apply standards regarding thermal bridges in a correct way.

5. Acknowledgements

This paper is part of the project; Klimatskal (building envelope) 2019, a project funded by The Development Fund of the Swedish Construction Industry and Skanska Sverige AB. The purpose of the project is to develop a method to evaluate energy- and moisture performance for building envelopes.

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Articles IV

PAPERS
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Hygrothermal conditions in exterior walls for passive houses in cold climate considering future climate scenario

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Abstract

Reduction of energy use constitutes as an important measure for climate change mitigation. Buildings today account for 40% of the world's primary energy use and 24% of the greenhouse gas emissions [1]. The concept of passive houses is one of many necessary measures for climate change mitigation. To reach the passive house ambition in cold climates, increased thermal resistance of the building envelope is vital. Increasing the thermal resistance in combination with climate change will result in a different microclimate within the building envelope.

Possible future micro climate in exterior walls are produced by hygrothermal simulations using the numerical software WUFI . The simulations are conducted for four different locations in Sweden, where the main difference is geographically in the respect of latitude, for the year period 1985-2098. Regional climate is based on data from the Swedish Meteorological and Hydrological Institute, using regional climate models developed at the Rossby Centre, RCA3. The RCA3 model covers Europe with a horizontal resolution of 50x50 kilometres. The boundary conditions are from the global climate model ECHAM5.

The increased risk for performance failure due to high humidity levels is conducted by assessing the result from the simulations combining three different evaluation models described in, which mainly differ in respect of the consideration of fluctuating hygrothermal conditions.

The investigations show that the risk of mould growth will increase in the future. However, adding more insulation to the exterior side of a wood frame construction results into more stabile hygrothermal conditions. Based on the results from the simulations it is recommended that all constructions with bio gradable materials should be given exterior insulation to decrease the risk of mould growth. Furthermore, building elements must always be designed to have the ability to dehydrate moisture that has entered, whether it is due to driving rain, built in moisture or other reasons.

Introduction

Published in 2007, the fourth assessment report [IPCC 2007] generated considerable attention as it through observations and measurements stated that there is a warming of the climate system. The observed temperature increase is wide spread all over the globe and is higher at northern latitudes. Furthermore, IPCC concludes that further warming is expected, and increases in the amount of precipitation are very likely in high-latitudes.

One of the drivers of climate change is Green house Gases, GHG. Buildings today account for 40% of the world's primary energy use and 24% of the GHGs [International Energy Agency (IEA) 2011]. As the world's population and need for buildings are growing; Reduction of energy use and a transition towards use of renewable energy in the building sector is vital.

A common approach to design and build an energy efficient building is to apply the passive house design principle where the first step is to reduce heat losses by constructing a well insulated and air tight building envelope in combination with balanced ventilation with high system heat recovery efficiency [Janson 2010].

Within the building construction industry, robustness and durability of building elements are often based on experience. The experiences are often expressed qualitatively, and not specified in quantitative terms. However, it is very likely that increasing the thermal resistance in combination with climate change will result in different hygrothermal conditions within the building envelope. Built in moisture will take longer time to dry out and the outer parts of building elements will have hygrothermal conditions more similar to the exterior climate. This might give a higher risk for mould growth.

This paper investigates the risk of performance failure due to mould growth, based on possible future climate scenario using three different evaluation models. The paper is a prolongation of a previous study [Berggren and Wall 2012] which will be presented at the 7th International Cold Climate HVAC Conference, hosted by

ASHRAE. One of the conclusions in the previous study was that built in moisture has a considerable effect on the risk of mould growth. To maintain consistency the present study is based on the same case wall constructions. The hypothesis of this study is that built in moisture and adsorbed water due to driving rain may have a great effect on the risk of performance failure.

Method

The case study

An exterior wall construction with standard amounts of insulation, U_c=0.17 W/m^{2}K, was compared to two alternative wall constructions with more insulation, U_c=0.09 W/m^{2}K. The standard case was an insulated wood frame construction, 170 mm, insulated with mineral wool. Exterior to the wood frame construction are; 13 mm wind shield/wind stabilization, 28 mm air gap and wood panel cladding. On the interior side of the wood frame construction are; vapour barrier, 70 mm insulated wood frame construction and 13 mm gypsum plasterboard. The difference between the two alternative wall constructions was where the increased amounts of insulations were mounted. In Alternative 2, the insulation was mounted on the interior side of the wood frame construction. In Alternative 3, the insulation was mounted partly on the exterior side of the wood frame construction, and partly on the interior side of the wood frame construction. The different wall assemblies are presented graphically in Figure 1 below.

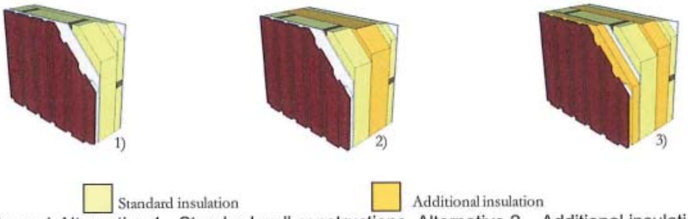
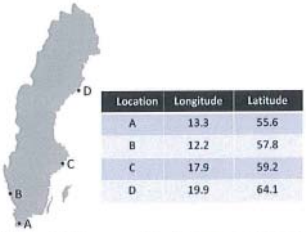


Figure 1 Alternative 1 - Standard wall constructions. Alternative 2 – Additional insulation on the interior side of the wood frame construction. Alternative 3 – Additional insulation on the exterior and interior side of wood frame construction

Investigation of hygrothermal conditions

To generate future climate scenario data for simulations, the imposed offset method was applied. There are different methods to generate future climate data for simulations and estimations of building performance in respect to climate change. Several studies and proposals have been published. These may be divided into four groups, from simple to complex; extrapolating statistical method, the imposed offset method, stochastic weather model and climate models [Guan 2009]. The imposed offset method bases the climate data on a typical year, meteorological – TMY, or reference – TRY. Known parameters that are expected to be affected by climate change are adjusted by offsetting the parameters based on the results from the climate models. This method has been used in many studies and has the benefit that it can be used even if changes of all parameters are not known. The Rossby Centre at the Swedish Meteorological and Hydrological Institute, SMHI, uses three-dimensional regional climate models that mathematically describe the climate system with a rather high resolution. In this case study the RCA3 [Samuelsson, Jones et al. 2011] model was used. The RCA3 model covers Europe with a horizontal resolution of 50x50 kilometers. The boundary conditions are from the global climate model ECHAM5 [Roeckner, Bengtsson et al. 1999]. In the previous study [Berggren and Wall 2012], climate scenario data were obtained for four different locations, based on the scenario A1B, in Sweden with monthly resolution for the period 1985-2098 [Swedish Meteorological and Hydrological Institute (SMHI) 2012]. The locations are given in Figure 2. The study showed that the most unfavourable conditions were location A and B. Hence location C and D are not included in this study.



Location	Longitude	Latitude
A	13.3	55.6
B	12.2	57.8
C	17.9	59.2
D	19.9	64.1

Figure 2 Geographical presentation of locations included in the study

The monthly mean deviation from the reference year, 1961-1990, was calculated for temperature, wind speed and precipitation. To generate input data for detailed simulations, reference years were generated with hourly resolution using Meteonorm 6.1 [Meteotest 2010]. These data were adjusted with the monthly deviation and compiled into longer time series. Adjustments in wind speed and temperature were made in absolute terms, increasing or decreasing the hourly data. Adjustment of precipitation was made by multiplying the hourly data with the monthly deviation in percentage.
Due to limitations in computing power, the investigated period has been divided into time series of three years, i.e. 1985-1987, …, 2096-2098.

Hygrothermal simulations were conducted using the numerical software WUFI Pro 5.1 1D [Fraunhof-Institut fur Bauphysik 2012]. The interior climate was seasonally varied according to EN 15026 [Swedish Standards Institute 2007]. A separate simulation was conducted for each three year period, specific location and wall assembly.

Evaluation models

Initiation of mould growth is difficult to predict. There are climate conditions documented under which mould growth is initiated. Examples may be found in [Viitanen 1997], [Johansson, Samuelson et al. 2005] and [Nilsson 2006]. However, these are usually based on constant hygrothermal conditions. In reality, hygrothermal conditions are fluctuating. In this study three different models are used to assess the risk of mould growth based on temperature and relative humidity (RH).

The Dose model

A performance model has been developed at Lund University in order to quantify the potential for mould growth [Isaksson, Thelandersson et al. 2010]. The model is based on the critical time, t_{ms}, for onset of mould growth, level 1, under different climate conditions (constant time) given by Equation 1, based on [Viitanen 1997].

$$t_{ms} = \exp(-0.74 \ln T - 15.53 \ln RH + 75.736) \qquad 1$$

Where T is the temperature in (°C) and RH is the relative humidity (%). The formula is valid for relative humidity in the interval $75 \leq RH \leq 100$ and temperatures $0.1 \leq T \leq 40$. By choosing a reference climate as T_{ref} = 20°C and RH_{ref} = 90%. Mould is in theory initiated after 38 days. The total mould dose, D, may then be described as in Equation 2 based on Equation 3, Equation 4 and Equation 5. Input data for calculations are daily averages.

$$D_n = \sum_{1}^{n} D_{RH}(RH) \cdot D_T(T) \qquad 2$$

Where D_n is the dose after n days, $D_{RH}(RH)$ is the dose component based on RH and $D_T(T)$ is the dose component based on temperature. The dose components are defined by derivation of Equation 1.

$$D_{RH} = \exp\left[15.53 \cdot \ln\left(\frac{RH}{90}\right)\right] \qquad \text{for} \qquad 75 < RH \leq 100 \qquad \text{3a}$$

$$D_{RH} = \left(-2.7 + \frac{1.1\text{RH}}{30}\right) \qquad \text{for} \qquad 60 < RH < 75 \qquad \text{3b}$$

$$D_{RH} = -0.5 \qquad \text{for} \qquad RH < 60 \qquad \text{3c}$$

$$D_T = \exp\left[0.74 \cdot \ln\left(\frac{T}{20}\right)\right] \qquad \text{for} \qquad 0.1 \leq T \qquad 4$$

$$D_T \cdot D_{RH} = -0.5 \qquad \text{for} \qquad T < 0.1 \qquad 5$$

Negative "doses" are added when conditions for mould growth is unfavourable [Isaksson, Thelandersson et al. 2010]. The accumulated mould dose, D_m, never falls below zero. To calculate the relative dose, the accumulated dose may be divided with the reference climate for which mould in theory is initiated, i.e. in this case 38 days. Mould is in theory initiated when the relative mould dose ≥ 1. To analyze the risk for mould growth, daily averages of relative humidity and temperature at the interior side of the wind barrier were extracted from WUFI Pro 1D and analyzed, using the "Dose model". As the mould dose varies within each 3-year simulation, the highest accumulated D, divided by 38, is displayed.

The m-model

The m-model was developed at Skanska Sverige AB to assess and compare different design solutions with respect to the risk of mould growth, also described in [Tengberg and Togerö 2010] and [Togerö, Tengberg et al. 2011]. The m-model is similar to the "Dose Model". The model also is based on calculating the critical time for when mould in theory is initiated. However, the m-model enables evaluations on shorter time steps, 1-3 hours, and uses six different duration curves for which mould in theory is initiated, as shown in Figure 3.

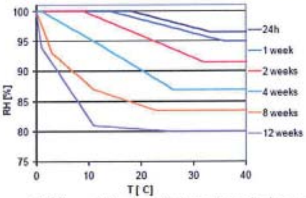


Figure 3 Six critical moisture levels based on [Viitanen 1996] and [Nilsson 2009] from [Togerö, Tengberg et al. 2011]

At each time step, a parameter called m is calculated according to Equation 6. This is calculated for all six critical duration curves.

$$m_{DC} = \frac{RH(t)}{RH_{crit}(T(t))\gamma} \qquad 6$$

Where m_{DC} is the *m parameter* for each duration curve, DC, based on the critical relative humidity, RH_{crit}, at the temperature T. This equation also includes a safety factor, γ, in this study 0.99. If m ≥ 1, conditions for mould growth have occurred in one time step. All time steps where m ≥ 1 are summarized separately for each DC, and constitute the accumulated risk time. The m-model considers dehydration according to Equation 7.

$$m_{DC,reduced} = \beta \cdot \sum m_{DC} \qquad 7$$

Where β is the retardation factor according to Equation 8.

$$\beta_{m_{DC,24h}} = \left(\frac{RH}{RH_{crit}}\right)^{4.5} \quad \text{for} \quad \frac{RH}{RH_{crit}} < 1 \quad >6\ \text{h} \tag{8a}$$

$$\beta_{m_{DC,1w,2w,3w}} = \left(\frac{RH}{RH_{crit}}\right)^{1.7} \quad \text{for} \quad \frac{RH}{RH_{crit}} < 1 \quad >168\ \text{h} \tag{8b}$$

$$\beta_{m_{DC,8w,12w}} = \left(\frac{RH}{RH_{crit}}\right)^{1.2} \quad \text{for} \quad \frac{RH}{RH_{crit}} < 1 \quad >168\ \text{h} \tag{8c}$$

$$\beta_{m_{DC,all}} = 0 \quad \text{for} \quad \frac{RH}{RH_{crit}} < 1 \quad >504\ \text{h} \tag{8d}$$

Where RH and RH_{crit} is average during the period for unfavorable conditions.
The accumulated risk time for each duration curve is divided with the critical risk time. The quota is called critical duration quota, CDQ. Mould will in theory be initiated when CDQ ≥ 1.0. To analyze the risk for mould growth, hourly values of relative humidity and temperature were extracted from WUFI Pro 1D and analyzed, using the "m-model". The same position for analysis was chosen as the one for the "Dose model". As within analysis using the Dose model, the risk of mould growth, CDQ, varies. The highest CDQ during each evaluated period and for all six calculations is displayed.

WUFI Bio

In addition to the software WUFI Pro, a plug-in to assess the risk of mould growth is available; WUFI Bio. This model differs from models described above. Within the model a hypothetical mold spore is given characteristics of diffusion of water vapour and sorption of water. If the water content within the mold spore exceeds critical levels [Sedlbauer 2001], mould growth is initiated. The pace of mould growth is related to the level water content. The model is described in [Sedlbauer 2001] and [Sedlbauer 2003]. The result of the evaluation is presented on a seven-point scale, presented in Table 1, defined by [Viitanen and Ritschkoff 1991]. The position of analysis was the same as used for the other models. The substrate class chosen was class 1, which corresponds to building products made out of biologically degradable materials.

Index	Description
0	No mould growth
1	Some mould growth, visible under microscope
2	Moderate mould growth, visible under microscope – coverage >10%
3	Growth detected visually, thin hyphae found under microscope
4	Visual coverage of mould growth >10%
5	Visual coverage of mould growth >50%
6	Visual coverage of mould growth 100%

Table 1 Mould index [Viitanen and Ritschkoff 1991]

Test of models and sensitivity analysis

For the three different case wall assemblies, Figure 1, a base case and a simple sensitivity analysis was carried out, focusing on built in moisture and rain penetration. A summary of the different set-ups are presented in Table 2.

Set up	Description	Varied parameters		Parameters not varied
		Built in moisture	Rain penetration	
α	Base case	Gypsum boards; 20 kg/m^3 Insulation; 4 kg/m^3	1 % of driving rain reaches wind shield	Cardinal direction; west Ventilation in air gap; 50 h^{-1}
β	Minimizing built in moisture	Gypsum boards; 10 kg/m^3 Insulation; 2 kg/m^3	1 % of driving rain reaches wind shield	Indoor climate; EN 15026, normal occupancy
γ	β + increased rain penetration	Gypsum boards; 10 kg/m^3 Insulation; 2 kg/m^3	5 % of driving rain reaches wind shield	Driving rain; (precipitation)x(wind speed)x0.07

Table 2 Summary of different scenarios

Results

Evaluation of hygrothermal conditions are presented in Figure 4, Figure 5 and Figure 6. Numbers represents the studied wall assemblies (1-3 according to Figure 1). Letters represents the geographical position (A & B according to Figure 2).

The "dose model" indicates that location B has much more unfavourable conditions compared to location A. The risk for mould growth for the wall assemblies at location A are relatively constant and not particularly affected by the climate scenarios when studying set-up α and β where the rain penetration was 1% of the driving rain. In these set-ups, wall assembly 2 (increased insulation without exterior insulation), receives the highest calculated relative mould dose. In set up γ, increased rain penetration, the wall assembly 3 (increased insulation with exterior insulation) receives the highest relative mould dose compared to the other set-ups. This is due to the external insulation (on the exterior side of the wind shield) which results in warmer conditions. Hence, this becomes more favourable for mould growth. If the built in moisture is minimized and the rain penetration is 1% (set-up β), all wall assemblies at location A and wall assembly 3 at location B receive a calculated relative mould dose ≤ 1.

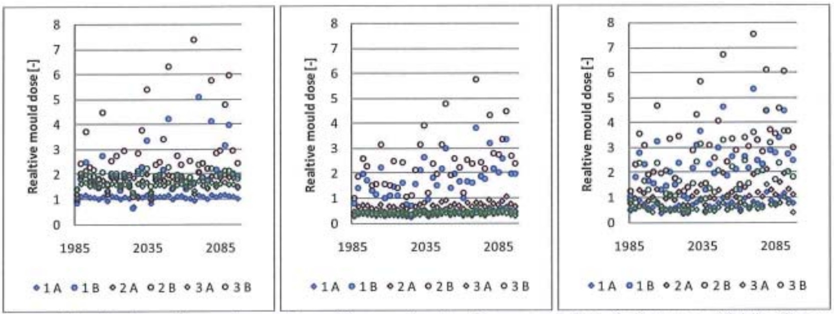


Figure 4 Evaluation of hygrothermal conditions using the "Dose model". Left; Set up α. Middle; Set-up β. Right; Set-up γ.

Using the m-model indicates the same results as when the dose model was used. However, there is a clearer trend of increased risks for mould growth due to climate change. Examining set up γ, increased rain penetration, some results show a higher risk of mould growth when exterior insulation is used compared to the other wall assemblies without exterior insulation. This result is not seen in the analysis using the dose model.

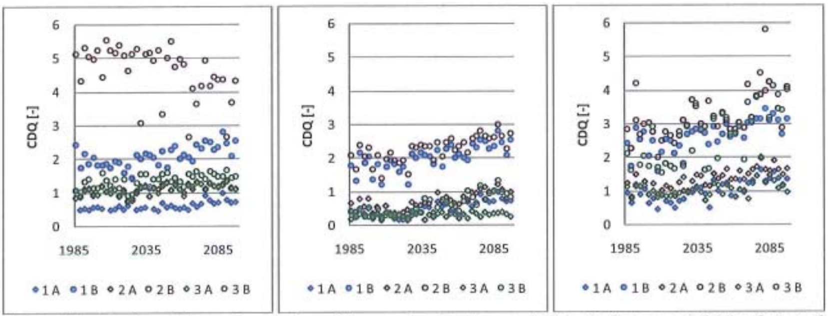


Figure 5 Evaluation of hygrothermal conditions using the "m-model". Left; Set-up α. Middle; Set-up β. Right; Set-up γ.

In difference compared to all other results, wall assembly 2 at location B and base case set-up, show a decreasing risk for mould growth for future climate scenarios. The reason for this has not been determined.

Using WUFI Bio results in a very clear indication that using external insulation and keeping the built in moisture to a minimum is favourable. Examining the set-up with low built in moisture and location B, wall assembly 3 show a very low mould index compared to wall assembly 1 and 2. WUFI Bio also indicates (as when the m-model was used) that external insulation may result in higher risk for mould growth if the rain penetration is high.

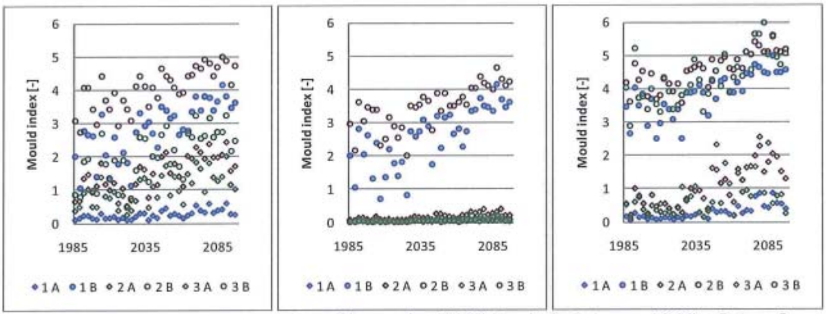


Figure 6 Evaluation of hygrothermal conditions using WUFI Bio. Left; Set-up α. Middle; Set-up β. Right; Set-up γ.

Discussion and conclusions

This study is based on one climate scenario. It is important to stress that climate models are used to simulate and produce climate scenario data. These climate scenarios are not weather forecasts. They are scenarios based on emissions scenarios from IPCC Special Report on Emissions Scenarios, SRES (IPCC 2000). The climate scenarios answer the question; - if the atmosphere is changing in a certain way, how will the climate change? The investigated scenario indicates that the ongoing climate change will most likely increase the risk of mould growth.

From this study, the major conclusions and recommendations are:

- Buildings are expected to have a long life-span. Therefore effects of climate change in the design of buildings and building elements must be considered.
- Construction materials based on bio gradable materials, e.g. wooden studs, should always be given exterior insulation to decrease the risk of mould growth. However poor assembly, i. e. enabling driving rain to penetrate exterior walls, most likely at junctions may actually increase the risk for mould growth.
- Within the construction phase of buildings, there is a need to implement all reasonable measures to decrease the amount of moisture, added in this phase.
- Building elements must be given de ability to dehydrate moisture that has entered, whether it is due to driving rain, built in moisture or other reasons.

Acknowledgements

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Articles V

Moisture Conditions in Exterior Walls for Net Zero Energy Buildings in Cold Climate Considering Future Climate Scenario

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Student Member ASHRAE

Maria Wall, PhD

ABSTRACT

An important measure for climate change mitigation is reduction of energy use in buildings worldwide. To decrease the energy use of a building in a Nordic climate, increased thermal resistance of the building envelope is a suitable measure. Adding more insulation in combination with climate change may increase the risk of mold growth within the building envelope. This study evaluates hygrothermal conditions for three different wood frame wall assemblies and four different locations in Sweden. The evaluation is based on simulations where the exterior climate is based on a climate scenario from the Swedish Meteorological and Hydrological Institute. The evaluation of the climate scenarios show a trend of increased precipitation and temperature. Examining the hygrothermal conditions; all evaluations models indicate an increased risk of mold growth over time due to climate change. Adding more insulation to a building envelope will decrease the dehydration of built-in moisture. However, adding more insulation to the exterior side of a wood frame construction results into more stabile hygrothermal conditions. Based on the results from the simulations it is recommended that all constructions with bio gradable materials should be given exterior insulation to decrease the risk of mold growth. Furthermore, building elements must always be designed to have the ability to dehydrate moisture that has entered, whether it is due to driving rain, built in moisture or other reasons.

INTRODUCTION

The fourth assessment report (IPCC 2007) presents, through observations and measurements, that there is a warming of the climate system. The increase of temperature is spread all over the globe but higher at northern latitudes. In addition to the warming, increases in the amount of precipitation in high-latitudes are very likely. One of the drivers of climate change is Green house Gases, GHG, where Carbon dioxide, CO_2, is the most important GHG.

Reduction of energy use constitutes as an important measure for climate change mitigation. Buildings today account for 40% of the world's primary energy use and 24% of the GHGs (International Energy Agency (IEA) 2011), Today, the concept of Net Zero Energy Buildings, Net ZEBs, is no longer perceived as a concept that only can be reached in a very distant future. A growing number of projects/buildings in the world, in different climate, show that it is possible to reach Net ZEB balance with technologies available today on the market (SHC Task40/ECBCS Annex52 IEA 2011; U.S. Departement of Energy 2011). To reach the Net ZEB balance in cold climates, increased thermal resistance of the building envelope is a fundamental measure. An overview of Net ZEBs worldwide (Musall, Weiss et al. 2010) shows that all investigated projects have applied the measure of increasing the amount of insulation in the building envelope.

Traditionally, durability and robustness of building elements are based on experience and are not specified in

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quantitative terms. However, increasing the thermal resistance in combination with climate change will result in different hygrothermal conditions within the building envelope. For example, in a Nordic climate the outer parts of a wall will have hygrothermal conditions more similar to the exterior climate as the thermal resistance increases and moisture may take longer time to dry out. This might give a higher risk for mold growth.

This paper focuses on investigating the risk of performance failure, due to mold growth, based on possible future climate scenario using four different evaluation models.

METHOD

Climate Scenario

Climate models are used to simulate and produce climate scenario data. Global climate models, GCMs, are representations of physical processes within and between the atmosphere, land surface, oceans and sea ice. GCMs require a lot of computing power. Therefore, the grid in global climate models usually has a sparse resolution and gives little detail on the regional and local scale. Regional climate models, RCMs, can be used to study specific areas in more detail, e.g. Europe. A small area makes it possible to have a denser grid, and consequently more detailed results. The boundary conditions for a RCM are coupled to a GCM. The Rossby Centre at the Swedish Meteorological and Hydrological Institute, SMHI, uses three-dimensional regional climate models that mathematically describe the climate system with a rather high resolution. In this case study the RCA3 (Samuelsson, Jones et al. 2011) model was used. The RCA3 model covers Europe with a horizontal resolution of 50x50 kilometers. The boundary conditions are from the global climate model ECHAM5 (Roeckner, Bengtsson et al. 1999). Climate scenario data were obtained for four different locations, based on the scenario A1B, in Sweden with monthly resolution for the period 1985-2098 (Swedish Meteorological and Hydrological Institute (SMHI) 2012). The locations are named A-D and corresponds to the following locations; A; Lund (55.6°N, 13.3°E), B; Göteborg (57.8°N, 12.2°E), C; Stockholm (59.2°N, 17.9°E) and D; Umeå (64.1°N, 19.9°E).

The monthly mean deviation from the reference year, 1961-1990, was calculated for temperature, wind speed and precipitation. To generate input data for detailed simulations, reference years was generated with hourly resolution using Meteonorm 6.1(Meteotest 2010). These data were adjusted with the monthly deviation and compiled into longer time series. Adjustments in wind speed and temperature were made in absolute terms, increasing or decreasing the hourly data; using the monthly average offset from reference year. Adjustment of precipitation was made by multiplying the hourly data with the monthly deviation in percentage.

Due to limitations in computing power, the investigated period has been divided into time series of three years, i.e. 1985-1987, …, 2096-2098.

The case study

An exterior wall construction with standard amounts of insulation, U_c=0.17 W/m^{2}K or R_{SI}=5.9 m^{2}K/W, was compared to two alternative wall constructions with more insulation, U_c=0.09 W/m^{2}K or R_{SI}=11.1 m^{2}K/W. The standard case was an insulated wood frame construction, 170 mm, insulated with mineral wool. Exterior to the wood frame construction; 13 mm wind shield/wind stabilization, 28 mm air gap and wood panel cladding. On the interior side of the wood frame construction; vapor barrier, 70 mm insulated wood frame construction and 13 mm gypsum plasterboard.

The difference between the two alternative wall constructions was where the increased amounts of insulations were mounted. In Alternative 2, the insulation was mounted on the interior side of the wood frame construction. In Alternative 3, the insulation was mounted partly on the exterior side of the wood frame construction, and partly on the interior side of the wood frame construction. The different wall assemblies are presented graphically in Figure 1 below.

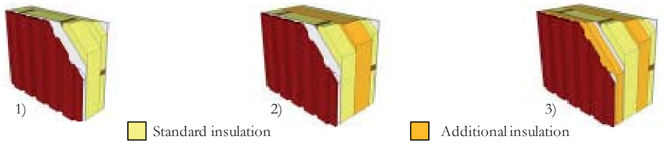

Figure 1 *(1) Alternative 1 - Standard wall constructions and (2) Alternative 2 – Additional insulation on the interior side of the wood frame construction (3) Alternative 3 – Additional insulation on exterior and interior side of wood frame construction*

Investigation of hygrothermal conditions

Hygrothermal simulations was conducted using the numerical software WUFI Pro 5.1 1D (Fraunhof-Institut fur Bauphysik 2012). The interior climate was seasonally varied according to EN 15026 (Swedish Standards Institute 2007). A separate simulation was conducted for each three year period, specific location and wall assembly. Relatively high initial moisture content was assumed in the simulations, 20 kg/m^3 for gypsum boards and 4 kg/m^3 for insulation, in order to account for built-in moisture during the construction phase. To enable detailed analysis of the relative temperature distribution within the constructions, all constructions were 3D-modeled in HEAT 3 6.0 (Blocon Sweden 2011) with a temperature difference of 1°C/1.8°F.

Evaluation models

The Dose Model. At Lund University a performance model has been developed in order to quantify the potential for mold growth (Isaksson, Thelandersson et al. 2010). The model is based on the critical time, t_{ms}, for onset of mold growth, level 1, under different climate conditions (constant time) based on (Viitanen 1997).

The accumulated mold dose is calculated and divided with the reference climate for which mold in theory is initiated. In this case the reference climate is set to 20°C/68°F and relative humidity, RH, to 90%. Mold will then in theory be initiated in 38 days. If the relative mold dose ≥1 mold is in theory initiated. To analyze the risk for mold growth, daily averages of RH and temperature at the interior side of the wind barrier were extracted from WUFI Pro 1D and analyzed, using the ”Dose model”. As the mold dose may vary over time, this study examines the risk of mold growth by displaying the highest accumulated D, divided by 38.

The m-model. The m-model was developed at Skanska Sverige AB to assess and compare different design solutions from a mold risk perspective and is further described in (Tengberg and Togerö 2010; Togerö, Tengberg et al. 2011). The m-model is similar to the ”Dose Model” since this model also is based on calculating the critical time for when mold in theory is initiated. However, the “m-model” enables evaluations on shorter time steps, 1-3 hours, and uses six different duration curves based on (Viitanen 1996; Nilsson 2009).

The accumulated risk time for each duration curve is divided with the critical risk time. The quota is called critical duration quota, CDQ. If CDQ≥1.0, mold will in theory be initiated. The highest CDQ during the evaluated period and all six calculations is displayed. To analyze the risk for mold growth, hourly values of RH and temperature were extracted from WUFI Pro 1D and analyzed, using the ”m-model”. The same position for analysis was chosen as the one for the “Dose model”.

The Hagentoft model. A simplified method for risk assessment was introduced by C-E Hagentoft at the 3rd Nordic Passive House Conference 2010 (Hagentoft 2010). The model uses a non-dimensional temperature factor, ξ, to calculate the RH at any point in a construction. For each month the calculated RH was divided by RH_{crit}. The highest value within each three year period, 1985-1987, …, 2096-2098, is presented. The specific position who was examined was the same as for the analysis conducted with the “Dose model” and the “m-model”.

WUFI Bio. In addition to the software WUFI Pro, a plug-in to assess the risk of mold growth is available; WUFI Bio. This model is different from models described above. Within the model a hypothetical mold spore is given characteristics of sorption of water and diffusion of water vapor. If the water content within the mold spore exceeds critical levels (Sedlbauer 2001), mold growth is initiated. The pace of mold growth is related to the level water content. The model is thoroughly described in (Sedlbauer 2001; Sedlbauer 2003). The result of the evaluations is presented on a seven-point scale defined by (Viitanen and Ritschkoff 1991). The position of analysis was the same as used for the other models. The substrate class chosen was class 1, which corresponds to building products made out of biologically degradable materials.

RESULTS

Climate scenarios

Summarized results from the climate scenario for the different locations are presented in Figures 3-5. For each location, the effect on temperature, precipitation and wind is presented based on five different indicators. Comparing the reference year, 1961-1990, to the average year for future climate, 1985-2100, the difference between them is small. The increase of temperature varies between 0.6 and 3.4°C (1.1 and 6.1°F). However, examining the maximum increase or decrease of temperature; the highest increase may be as high as 9°C/16.2°F, and decrease 7°C/12.6°F. The increase in temperature is slightly higher at northern latitudes.

The monthly average wind speed and maximum offset compared to reference year are considerably higher at location A compared to the other examined locations. At all locations the wind speeds are higher in winter compared to summer. A very small increase of average wind speed is expected in the examined climate scenario.

The monthly average precipitation is increasing at all locations. The maximum monthly average is expected in fall at all locations, exceeding 200 mm of precipitation.

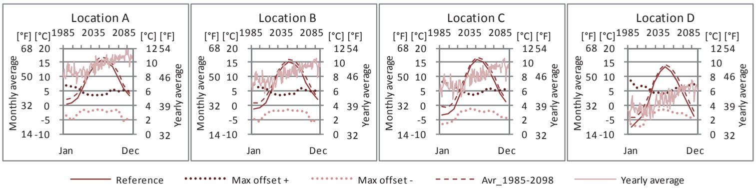

Figure 3 *Climate scenario; Temperature. All data, except Yearly average, refer to the bottom x-axis and left y-axis. Yearly average refers to the top x-axis and right y-axis.*

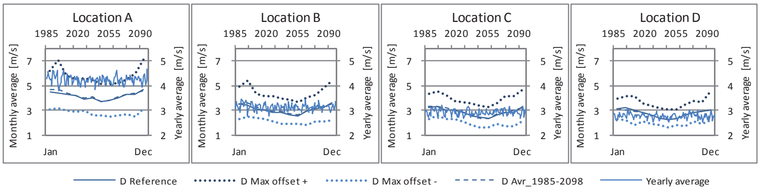

Figure 4 *Climate scenario; Wind. All data, except Yearly average, refers to the bottom x-axis and left y-axis. Yearly average refers to the top x-axis and right y-axis.*

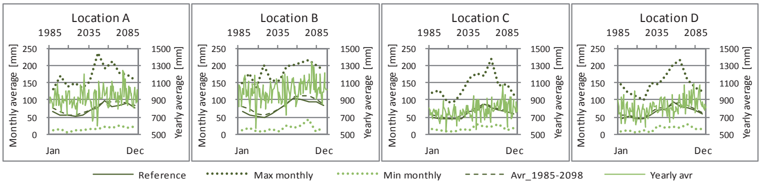

Figure 5 *Climate scenario; Precipitation. All data, except Yearly average, refers to the bottom x-axis and left y-axis. Yearly average refers to the top x-axis and right y-axis.*

Results from the case study

Evaluations of hygrothermal conditions are presented in Figures 6-9. In these figures, 1A-1D represents the standard wall assembly. 2A-2D represents Alternative 2 where insulation was added on the interior side of the wood frame construction. Furthermore, 3A-3D represents Alternative 3 where insulation was added both on the interior and exterior side of the wood frame construction. For all wall assemblies the suffix A-D represents the specific location.

The highest calculated relative mold dose, D, for each three year period, location and wall assembly is presented in Figure 6. Using the "Dose-model" to analyze the hygrothermal conditions, the conditions for mold growth is increasing over time regardless of location and construction. The increase is somewhat more evident in the wall assembly where more insulation is added to the interior side of the wood frame construction.

When adding more insulation to the exterior side of the wood frame construction, more stable hygrothermal conditions occur. For the worst conditions, location B, the mold dose decreases even though more insulation is used in the construction. For the other locations the mold dose is increasing when more insulation is added. For location A and B, adding insulation to the exterior side of the wood frame construction decrease the mold dose compared to adding insulation to the interior side.

The CDQ, calculated using the m-model, shows a small increased risk of mold growth for the standard wall assembly over time for location A, see Figure 7. However, except for three simulations, CDQ≤1 for all simulations. For location C and D; the CDQ is low, except for three simulations where CDQ≥1. For C and D; the CDQ is decreasing over time for the standard wall assembly. For location B, all simulations result in CDQ≥1 and the increase of CDQ is clear for this location.

Except for location B, adding more insulation results into a clearer trend of increasing CDQ over time. For location A, the CDQ is lower if exterior insulation is used but CDQ exceeds 1 roughly around year 2030. At the more northern latitudes, C and D, CDQ is always below 1 regardless of construction chosen and examined year.

Comparing results based on "Dose-model" and "m-model", adding insulation to the exterior side of the wood frame construction result in more stabile hygrothermal conditions for all locations. For unfavorable climate with high RH, location B, a clear decreased risk of mold growth is also shown.

The highest mold index from WUFI Bio for each simulation is displayed in Figure 8. In this evaluation, the increase of mold is clearer over time compared to previous evaluations, especially when more insulation is added. This evaluation confirms the previous conclusion; adding insulation to the exterior side of the wood frame construction is especially favorable in location B. However, for all locations the mold index is lower in alternative 3 compared to alternative 2. In locations C and D. Mold index is almost always <1, regardless of wall assembly.

The Hagentoft model, based on monthly averages, shows increased risk of mold growth over time based on the climate scenarios. Furthermore, it indicates that exterior insulation is preferable in location A but has little effect on other locations.

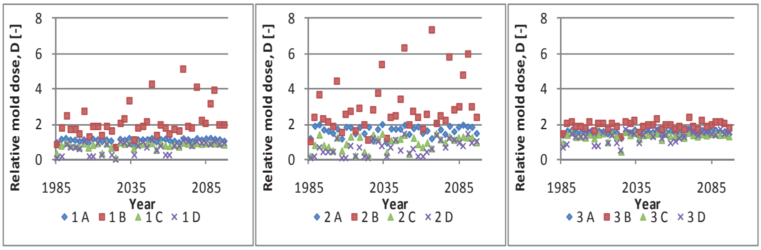

Figure 6 Evaluation of hygrothermal conditions using the "Dose-model".

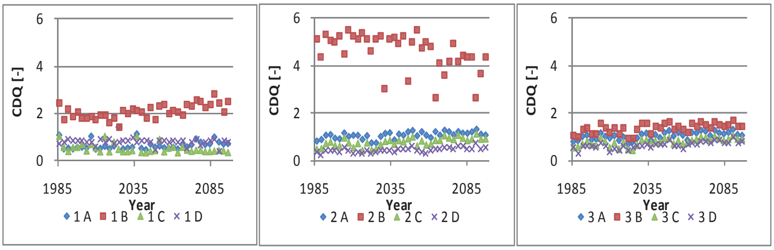

Figure 7 Evaluation of hygrothermal conditions using the "m-model"

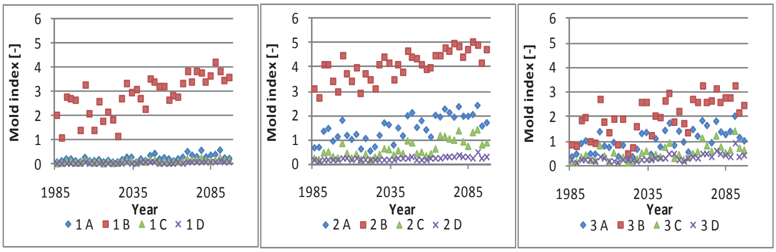

Figure 8 Evaluation of hygrothermal conditions using WUFI Bio

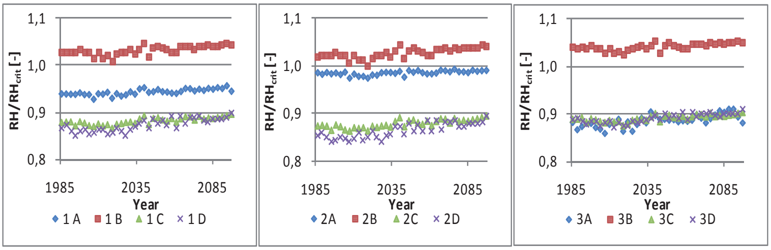

Figure 9 Evaluation based on the Hagentoft model

For location A and B, the risk of mold growth is high, regardless of wall assembly. To investigate the effect of built in moisture, the accumulated mold dose was studied in detail for location A and location B, the most unfavorable locations. The period was chosen to 2048-2050. The accumulated mold dose, D, is presented in Figure 10.

At location A, the built in moisture affects the accumulated mold dose, which rather fast exceeds the critical condition of 38 days. When more insulation is added, the dehydration of the construction takes longer time, resulting in a long period for which the accumulated mold dose exceeds 38 days. However in spring 2050, when unfavorable conditions once more occurs; the wall assembly with exterior insulation gets the lowest accumulated mold dose.

At location B, the exterior climate has a high relative humidity and lower temperature over the period. The built in moisture therefore takes longer time to dry out. The consequence is high accumulated mold dose. However, the wall assembly with exterior insulation, 3B, shows a slowly decreasing mold dose. Furthermore, when the very unfavorable conditions occur in spring 2050, the exterior insulation ensures that accumulated mold will not increase as much as for alternative 1 and alternative 2.

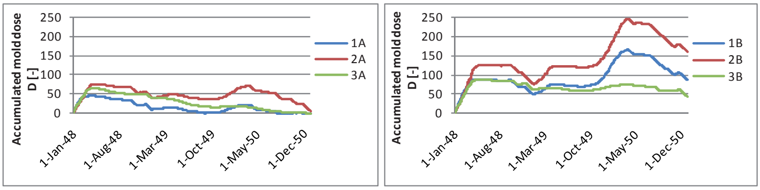

Figure 10 Accumulated mold dose for location A and B, wall assemblies 1, 2 and 3

DISCUSSION AND CONCLUSIONS

This paper is based on one climate scenario. Other climate scenarios may show similar or different results. Furthermore, a climate scenario is not a forecast, i.e. it is not the expected climate conditions, it is a climate scenario. All results in this paper must be interpreted with this in mind. However, some conclusions may still be made.

The investigated scenario indicates that the ongoing climate change will most likely increase the risk of mold growth. Except for two evaluations, 1C and 2B, evaluated with the m-model, all other evaluations indicate increased risks for mold growth due to climate change.

At first a fist glance; the interpretations of the evaluations of different locations, using different evaluation models may be that increased amounts of insulation is equal to higher risks for mold growth. This is due to that values presented in Figures 6 - 9 are maximum values. Examining the hygrothermal conditions in detail, as in Figure 10; it is possible to see that the built in moisture is the major reason for high risks of mold growth. When the built in moisture has dehydrated; the wall assembly with insulation on the exterior side of the wood frame work, is the most robust wall assembly.

From this study, the major conclusions and recommendations are:

- There is a need to consider the effects of climate change in the design of buildings and building elements in cold climate.
- Within the construction phase of buildings, there is a need to implement all reasonable measures to decrease the amount of moisture, added in this phase.
- Construction materials based on bio gradable materials, e.g. wooden studs, should always be given exterior insulation to decrease the risk of mold growth.
- Building elements must be given de ability to dehydrate moisture that has entered, whether it is due to driving rain, built in moisture or other reasons.

Evaluations based on simulations with hourly data showed higher risks and larger spreading of the calculated risks. Therefore, more studies are recommended to gather climate scenario data with higher time resolution and where more parameters are included, e.g. relative humidity, cloud cover etc., suitable for hygrothermal simulations.

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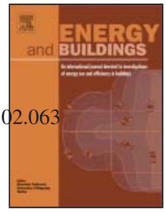
Articles VI



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LCE analysis of buildings - Taking the step towards Net Zero Energy Buildings

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Abstract

The basic concept of a Net Zero Energy Building (Net ZEB) is that on-site renewable energy generation covers the annual energy load.

The main objective of this study is to analyze the increase of embodied energy compared to the decrease of the energy use related to building operation; partly by a literature review, partly by detailed analysis of eleven case studies; taking the step from a low energy building to a Net ZEB. The literature review shows that the metric of evaluation, assumed life-span, boundary conditions, age of database and the origin of database differ in different studies and influence the result of embodied energy. The relationship between embodied energy and life cycle energy use is almost linear for all cases studied herein. During the last two decades, embodied energy in new buildings has decreased slightly. However, the relative share of embodied energy related to life cycle energy use has increased. The detailed life cycle energy analysis show that taking the step from a low energy building to a

Net ZEB results in a small increase of the embodied energy. However, the energy savings achieved in the annual operating energy balance clearly exceed the increase in embodied energy.

Highlights

> LCE analysis of Net Zero Energy Buildings

> The changing role of embodied energy

> Important parameters to address in the context of a life cycle energy analysis.

> Annual energy savings achieved for Net ZEBs, clearly exceed the increase in embodied energy.

Keywords

Net zero energy building; Embodied energy; Operation energy; Life cycle energy; Primary energy

1. Introduction

Today a number of buildings exist for which the design principle has been to achieve a Zero Energy Building (ZEB) or Net Zero Energy Building (Net ZEB) [1-6].

There are many different approaches and definitions of the two concepts. In general, the ZEB concept may be described as an autonomous building which does not interact with any external energy supply system (grid) such as district heating network, gas pipe network, electricity grid or likewise. The Net ZEB concept is a building where the weighted supply of energy from the building meets or exceeds the weighted demand and interacts with an energy supply system (grid). Such a building can export energy when the building's system generates a surplus and import energy when the building's system is insufficient to generate the energy required. The scope of the energy balance for the Net ZEB may vary for different concepts but is usually based on an annual balance of primary energy [7]. It is not always clear, however, whether this refers to total primary energy or non-renewable primary energy. Within this paper, the term; "primary energy use" is used when it is not clear whether the source refers to total primary energy use or non-renewable primary energy use.

This paper focuses on Net ZEBs. In Net ZEB definitions, there may or may not be a maximum limit on energy demand. The requirements are generally that the demand is covered by renewable energy sources and that the building is in compliance with the national standards and regulations. However, to meet the goal, a low demand gives an advantage. The general approach to reach Net ZEB could be described as a two-step concept. The first step is to reduce the energy demand by applying energy efficiency measures. The second step is to supply energy, generated by renewable sources, which may be supplied into an external grid when favourable [8-11]. This is illustrated in Fig 1.

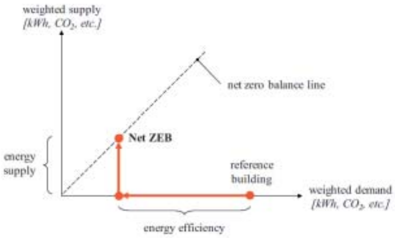

Fig. 1 Schematic presentation of demand/supply balance of a Net ZEB [11].

Reduction of energy demand has been promoted worldwide for some time and the techniques used have been applied in Passive Houses and low energy houses for many years and are adapted in the most known Net ZEBs [12]. The basic principle in heating dominated climates may be summarized as design and construction of a well insulated and airtight building envelope in combination with balanced ventilation with high heat recovery efficiency [13-15].

When the energy use of a building is discussed from a lifecycle perspective, it is today generally alleged that energy use in the operational phase of buildings accounts for 70-90% of energy used during its life cycle. There are a number of substantiated and extensive studies with results supporting that allegation [16-20]. Those studies differ in regard to calculation methodology used to account for the total energy use, Life Cycle Energy (LCE), but they reach similar conclusions which support the statement above. However, the consequence is that for Net ZEBs the relative share of energy use related to building operation will decrease.

Earlier studies have mainly focused on embodied energy in buildings with energy performance more or less equal to national building regulations or low energy buildings. An Italian study [21] compared a standard house and a low energy house, clearly showing the changing role of embodied energy in relative terms. The non-renewable primary energy use for construction and maintenance increased by 20 % when taking the step from the standard house to a low energy house. However, the relative share of embodied energy of the total life cycle energy use increased from 17 % to roughly 50 %.

Sceptics to the Net ZEB concept might even argue that the energy savings achieved related to building operation of a Net ZEB is lower compared to the increased energy use for production, maintenance and demolition. A German study [22] compared different concepts for a building; built according to building regulations, low-energy house, Passive House and ZEB for a lifespan of 80 years. In general, the life cycle energy use decreased for each step taken towards the Passive House standard. Taking the step to the ZEB, the life cycle energy use increased. The life cycle energy use of a ZEB consists of embodied energy only. Due to the very high technical level of the ZEB, mainly due to the need of large energy storage system, the life cycle energy use of a ZEB is higher compared to a Passive House.

It may be argued that the German study is inconsistent since the life cycle energy use for the ZEB includes all embodied energy for the building's on-site generation and energy storage systems, whereas the embodied energy of the grid supplying the Passive House with energy is not included in the life cycle energy balance comparison.

The main purpose of the study presented in this paper is to analyse the embodied energy where the focus is on the impact on the total life cycle energy use when the step is taken from a low energy building to Net ZEB instead of ZEB and to highlight important parameters that the authors believe should be addressed in the context of a life cycle energy analysis.

Life cycle energy analysis is one way of conducting Life Cycle Assessment (LCA). Other ways to assess the environmental impact of buildings may be to calculate the carbon footprint or Life Cycle CO_2 (LC CO_2). Some studies combine the evaluation of life cycle energy use with calculation of global warming potential, ozone emissions, carbon foot print, etc. [21, 23, 24]. The relative impact of different measures will change when applying different methodologies. Especially, this can be seen in [23, 24], where the energy analysis is not based on primary energy. Analysing conversion factors for CO_2-equivalents and primary energy, presented in [11], the ratios are more alike when comparing factors for non-renewable primary energy and CO_2-equivalents than compared to ratios between factors for total primary energy and CO_2-equivalents. However, differences still occur; comparing ratios for non-renewable primary energy and CO_2-equivalents. For example, non-renewable primary energy factors for oil and natural gas are roughly the same, whereas the factors for CO_2-equivalents for oil are roughly 20 % higher compared to natural gas. In this study, the metric; non-renewable primary energy is in focus. This is due to that data from previous studies generally were given as primary energy. Specifically, non-renewable primary energy was chosen to better reflect the environmental impact in form of CO_2-equivalents.

Table 1 shows a list of nomenclature used in this paper.

Table 1 Nomenclature used in this paper

ZEB	Zero energy building, autonomous building
Net ZEB	Net zero energy building, all energy as defined in EN 15603 [25] included
Net ZEB_L	Net zero energy building, limited balance; energy for lighting and other services are excluded
LCE	Life cycle energy
LCA	Life cycle analysis
EE	Embodied energy ($EE = EE_i + EE_r + DE$)
EE_i	Initial embodied energy
EE_r	Recurring embodied energy
DE	Demolition energy
OE	Operating energy. Net energy use related to building operation
HP	Heat pump
PV	Photovoltaic
ST	Solar thermal
EPR	Energy payback ratio
EPT	Energy payback time
NER	Net energy ratio

2. Methodology

2.1 Literature review

The literature review was conducted by reviewing peer-reviewed papers and through a survey among participating researchers of the IEA SHC Task40/ECBCS Annex52 “Towards Net Zero Energy Solar Buildings”, asking for case studies where LCE analyses were conducted and for information on country specific strategies for LCE analysis.

The purpose of the literature review was threefold;

- Identifying parameters which were handled differently in the studies
- Studying different databases, tools and rating systems used today
- Gathering LCE analysis data to enable analysis of the embodied energy as a relative share of life cycle energy use and the changing role of embodied energy.

All data were normalized into kWh/(m^{2}a). Only data based on primary energy were used, and where all energy use related to building operation was included in the operating energy (OE). However, primary energy factors used were not always presented and it was not always clear whether the data were in total primary energy or non-renewable primary energy. Furthermore, it was not always clearly stated what parts of the energy use were included in operating energy.

2.2 Detailed analysis of Minergie-A buildings

The Minergie® concept was developed in 1994 and since 1998 the Minergie® association has worked continuously to define and promote energy efficient buildings [26]. The Minergie institute has defined three different labels/definitions of energy efficient buildings where Minergie-A [27] is the latest standard for residential buildings, implemented in 2011. A Minergie-A building has a heating demand ≤ 90 % of the allowed heating demand according to the Swiss building regulations [28]. Also, a net zero energy balance for space heating, domestic hot water and ventilation is required, based on weighted energy carriers defined in [27]. If the energy carrier for heating is wood and more than 50% of the space heating and domestic hot water is covered by solar thermal collectors, a credit of 15 kWh/(m^{2}a), weighted energy, is given. It is required to calculate embodied energy, which must not exceed 50 kWh/(m^{2}a), non-renewable primary energy. Energy efficient white goods are required.

Minergie-A buildings are appropriate examples to evaluate the step towards Net ZEBs. They are Net ZEB$_L$ balanced, e.g. energy for plug loads and lighting is not included in the requirements.

In this study, the embodied energy of Minergie-A buildings includes the superstructure, building envelope and the HVAC system. The calculation of embodied energy was carried out based on data from the Bauteilkatalog [29]. Embodied energy data within Bauteilkatalog includes energy for replacement when the expected service life time expires and energy for demolition is included (cradle to grave analysis). Hence, the total life cycle energy use is analysed.

Further analysis focused on studying the effect on embodied energy and operating energy due to photovoltaic panels (PV panels), and solar thermal collectors. All buildings were redesigned and recalculated to examine the effect of taking the step towards Net ZEB, using a three-step approach:

- Buildings' redesigned and recalculated without PV panels (Low energy standard).

- Buildings' redesigned and recalculated with enough PV panels to meet a Net ZEB_L balance.
- Buildings' redesigned and recalculated with enough PV panels to meet a Net ZEB balance.

When data was extracted from the data base (July 2011) [30], a total of 11 buildings had applied for Minergie-A certification. For this study, all data for the Minergie-A buildings were recalculated with Swiss weighting factors for non-renewable primary from SIA 2031 [31], Table 2.

Table 2 Swiss weighting factors for non-renewable primary energy [31]

Energy carrier	Weighting factor, non-renewable primary energy [-]
Electricity	2.52
Wood	0.05
Pellets	0.21
District heating	0.79
Oil	1.23
Natural gas	1.14

Operating energy use for plug loads and lighting are not included in the Minergie® calculations. To enable analysis including the total operating energy, energy for lighting and plug loads was included in the energy demand. This results in an additional OE of 51.7 kWh/(m^2a), non-renewable primary energy. This estimation is based on a mean value of 20.5 kWh/(m^2a) of delivered electricity, measured for plug loads and lighting in 16 Passive House dwellings in Sweden [15].

3. Results and discussion

3.1 Literature review

Within the literature review, a total of 143 case studies were collected [19-20, 32-45]. Out of these cases studies, 73 cases were summarized in tabular form in [20]; clearly showing the embodied energy, operating energy and life cycle energy use. A summary of the data for the additional 70 cases is presented in Appendix A, following the same principle to enable comparison. Furthermore 11 case studies were gathered from the Minergie-A database [30], making a total of 154 cases available for analysis.

The basic framework for calculation of life cycle energy (LCE) use was defined differently in different studies. The overall goal, however, was to calculate the sum of all energies incurred in the life cycle of the studied project and/or building. The life cycle energy use may be defined as in Equation 1 according to Ramesh et al [20] or as graphically described by Dixit et al [46]. Comparing the two, one can see that the overall framework is the same.

$$LCE = EE_i + OE + EE_r + DE \qquad (1)$$

where LCE is the total life cycle energy use, EE_i is the initial embodied energy, OE is the operating energy, EE_r is the recurring embodied energy and DE is the demolition energy.

3.1.1 Country strategies for embodied energy

Today, no country has requirements regarding embodied energy requirement for buildings. Some countries have developed non-mandatory standards [47-49] that could be incorporated as a baseline in a building rating system. Many rating systems enable a possibility to include the environmental impact of building materials in the assessment of a building's environmental impact [26,50-58]. However, only two of twelve Net ZEB definitions reviewed in [7] consider including embodied energy in the Net ZEB balance.

A common barrier for all countries is the lack of a national matured and agreed database for building materials. Within Europe, there are two commonly used, extensive databases; Ecoinvent [59] and GEMIS [60]. However, other databases exist, e.g. [61-65], and a lot of different tools are available to calculate embodied energy, global warming potential, impact of the environment and other parameters for construction materials and assemblies, e.g. [29, 66-68].

On a European transnational level, an European Ecolabel and Green Public Procurement (GPP) criteria for buildings is being developed [69]. Within the European Commission, the Joint Research Centre, a web based platform has been developed where guidelines, tools and life cycle data are published [70].

3.1.2 Metrics used in the LCE-analysis

To ensure transparency and consistency, the applied metric for LCE analysis should be primary energy. Dixit et al. [46] concludes that inclusion of delivered energy in LCE analysis creates complications.

Delivered energy may also be referred to as final, end-use or un-weighted energy [7].

Within [19] 45 of 60 cases are presenting operating in primary energy. It is however not always clear whether the term primary energy refers to total primary energy or non-renewable primary energy.

As mentioned in the introduction, some studies combine the evaluation of life cycle energy use with calculation of global warming potential, ozone emissions etc. These types of analyses together with LCE analysis are different types of Life Cycle Assessments (LCAs). The difference between LCA and LCE analysis is that within LCA many different indicators may be used in the evaluation. In LCE, the indicator is always energy. The calculated life cycle energy use is usually divided by an assumed life-span of the building and the conditioned area. Hence the indicator is given in kWh/(m^2a).

3.1.3 Life span in LCE-analysis

When the result from the LCE analysis is presented in kWh/(m^2a), the expected life-span has no impact on the analysis of operating energy, in absolute terms, if the analysis is based on a simulation of the annual energy use and assumes that the energy supply system, extraction of raw materials for energy generation etc. do not change over time. However, it may have a significant impact on initial embodied energy and demolition energy as this is based on activities that occur once (energy for replacement, recurring embodied energy, may occur more or less than one time) and the energy use is divided by the assumed life-span.

The life-span used in the different studies varies between 30 and 100 years. Out of the 154 different cases, the average life-span is 53 years and the median is 50 years. In Fig. 2, the allocation of the different case studies is shown; the most used life-span is 50 years.

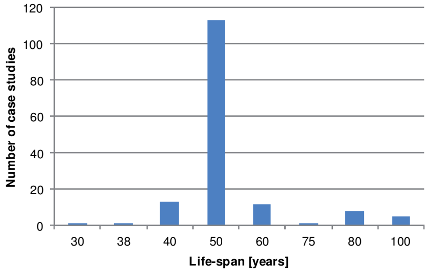

Fig. 2 Allocation of different case studies based on the applied life-span in the 154 different case studies.

3.1.4Boundary conditions for the LCE-analysis

A common problem in LCE analysis is to acquire all data coupled to the life cycle. The system boundary may be set where the data collection is getting too difficult and may therefore be strongly related to availability of research resources.

Differences may be found whether demolition, recycling, feed-stock energy and renovation are included. Furthermore, no analysis in the studied material seems to include furnishings. Adalberth [16] and Blengini et al [21] include white goods and sanitary ceramics in addition to materials included in the structural elements, building envelope and HVAC-system. Suzuki et al [71] and Cole et al [72] are two examples of studies with focus on the materials included in the structural elements, building envelope and HVAC-system.

Studies sometimes refer to life cycle energy use as the sum of embodied energy and operating energy. This may indicate that demolition energy is excluded in the analysis or included in the embodied energy. E.g. in [73] a LCE analysis is presented, excluding demolition energy. In [74] life cycle energy use refers to the sum of embodied energy and operating energy, including demolition energy in the embodied energy. However, the effect of energy use during demolition is often small. In [16] the relative share of energy use due to demolition was <1% of the total life cycle energy use. In [17, 21, 75] the energy use during demolition was negative, i.e. the energy extracted from the materials through recycling and combustion exceeded energy needed for disassembly. Hence, differences between different studies due to including or excluding demolition energy may be expected to be small.

Based on differences in the reviewed studies it is possible to divide the boundary conditions into two main categories:

- Boundary conditions regarding downstream and upstream processes
- Boundary conditions regarding material included in the analysis

To address the second category and to enhance transparency in the LCE-analysis, one may separately analyze the embodied energy of a measure taken to improve the operating energy use of a building. This approach is based on a marginal utility approach and assumes that the building or buildings that are analyzed is/are to be built anyway. It is therefore sufficient to analyze the specific effect of different measures in relation to a reference case in order to find good measures from a LCE perspective. This may be implemented in different ways.

Leckner et al [45] use two different indices in LCE-analysis; Energy Payback Ratio, EPR, and Energy Payback Time, EPT. The indices are described in Equation 2 and Equation 3.

Hernadez et al [76] suggest the use of a similar index as EPR called Net Energy Ratio, NER. The difference between the two indices is that EPR is based on the total changes over the life cycle and NER is based on the annual change, Equation 4. If the operating energy use is based on a simulation of the energy demand and assumes that the energy supply system, extraction of raw materials for production of energy etc. do not change over time, EPR and NER will have the same quota. The NER may also be referred to as Energy Yield Ratio or Energy Return of Investment.

$$EPR = \Delta OE_T / \Delta EE_T \qquad (2)$$

where EPR is the energy payback ratio for a specific measure, ΔOE_T is the total life cycle difference of operating energy due to the specific measure and ΔEE_T is the total difference of embodied energy due to the specific measure.

$$EPT = \Delta EE_T / \Delta OE \qquad (3)$$

where EPT is energy payback time for a specific measure and ΔOE is the annual difference of operating energy due to the specific measure.

$$NER = \Delta OE / \Delta EE \qquad (4)$$

where NER is the net energy ratio for a specific measure and ΔEE is the annual difference of embodied energy due to the specific measure.

3.1.5 Age of data

Energy use means capital expenditures. Therefore, in the production and distribution of materials and components the industry is always looking for cost-efficient ways to streamline and decrease the energy use. As a natural consequence, age of data has a large impact on the result of an analysis. A good example of where the market has decreased costs and decreased energy use is the production of Crystalline Silicon PV modules. In [77] the overlap between price and energy pay-back time of Crystalline Silicon PV modules were presented. The study showed that the EPT of PV modules decreased from 20 years, in the 1970s, to below five years, in 2005.

3.1.6 Different data bases

As mentioned in Section 3.1.1, a number of tools and databases that can be used to compile and analyze embodied energy for buildings are available today. Dixit et al [46] highlight and discuss the source of data as an important parameter that influences the result in embodied energy analysis.

Villa et al [44] present five case studies in which three different databases have been used (Case studies 43-58 in Appendix A, Table A.2). A comparison of the results of calculated embodied energy show a percentage difference of 15% - 87% for the different case studies due to use of different databases. The authors conclude that an important contributing factor to the differences is different methods used to quantify embodied energy for wooden products in databases used in their analysis.

The differences in the data bases are in general due to the above-named parameters and due to specific conditions regarding energy-mix, fabrication methods and transportation.

3.2 Analysis of case studies

Results given in this section are based on all 154 cases studies.

In Fig. 3 the relationship between operating energy and life cycle energy is presented for all cases from the literature review together with data from Minergie-A buildings [20, 30, 32-45]. In Fig. 4, case studies with operating energy>100 kWh/(m^2a) are excluded. The relationship between operating energy and life cycle energy is almost linear. This data correspond well with the earlier, highlighted, linear relationship in [19, 20]. The negative values of operating energy occur if the energy supply exceeds the energy demand.

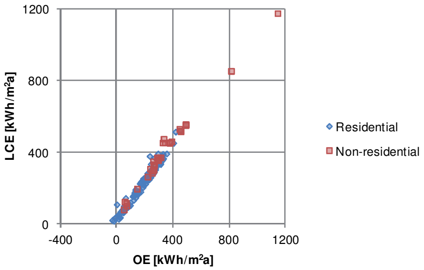

Fig. 3 Relationship between operating energy (OE) and life cycle energy (LCE), primary energy. All 154 case studies are included.

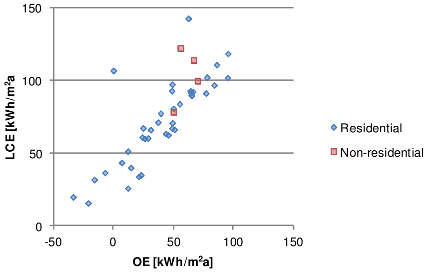

Fig. 4 Relationship between operating energy (OE) and life cycle energy (LCE), primary energy. Case studies with OE<100 kWh/(m^2a).

Low energy buildings and Net ZEBs usually requires more material in form of insulation and installations (PV panels, solar thermal collectors, heat pumps etc.). Hence it could be logical to assume that the linear relationship between operating energy and life cycle energy would flatten out. However the tendency is that the linear relationship is constant. This may be due to that design and construction often has a focus on sustainable material management. Furthermore, PV panels and solar thermal collectors generate more energy during building operation, compared to the embodied energy. It may also be partly due to that newer buildings show a tendency of a lower embodied energy compared to older buildings, see Fig. 5. The decrease could be due to more efficient use of materials and more efficient manufacturing.

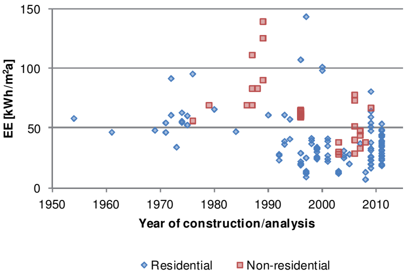

Fig. 5 Embodied energy (primary energy) by year of construction.

In Fig. 6 and Fig. 7 the relationship between the operating energy and the embodied energy as percentage share of life cycle energy use is presented together with an exponential regression for residential buildings and non-residential buildings. As there are no case studies for non-residential buildings where operating energy$\leq$0 kWh/(m^2a), data for a fictitious building have been incorporated.

Using the exponential regression formulas, the embodied energy exceeds 50% of life cycle energy use when the annual operating energy use is $\geq$33 kWh/(m^2a) and $\geq$45 kWh/(m^2a) for residential and non-residential buildings respectively. It may occur as strange that embodied energy as a share of life cycle energy exceeds 100% when the operating energy < 0 kWh/(m^2a). The effect is due to buildings that annually supply more energy than the annual energy demand, every year generating a surplus and thus reducing the total life cycle energy use.

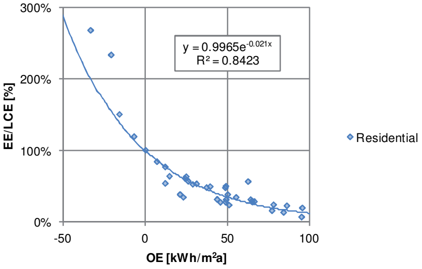

Fig. 6 Relationship between OE and EE/LCE (primary energy) for residential case studies with OE<100 kWh/(m^2a).

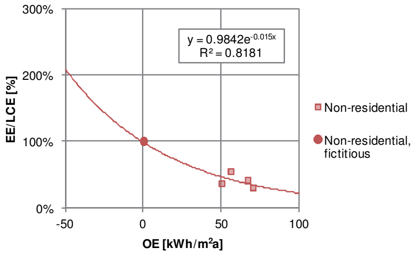

Fig. 7 Relationship between OE and EE/LCE (primary energy) for non-residential case studies with OE<100 kWh/(m^{2}a).

3.3 Detailed analysis of Minergie-A buildings

3.3.1 Characteristics of Minergie-A buildings

A summary of the gathered data from the Minergie-A database is presented in Table 3. All cases are residential buildings. Three stakeholders outperform the Minergie-A requirement of Net ZEB$_L$ balance, with the goal to reach Net ZEB balance (Case studies 71, 74 & 77).

All case studies have installed PV panels. Except no 76, all buildings have applied energy efficiency measures similar to a Passive House design with advanced thermal insulation and ventilation with heat recovery. Buildings without heat pump (HP), have installed pellet-/wood boiler. None of the Net ZEB buildings have installed heat pump.

Table 3 Summary of characteristics for Minergie-A buildings [30]

Case study	Gross area [m^2]	Life span	EE [kWh/(m^{2}a)]	OE [kWh/(m^{2}a)]	LCE [kWh/(m^{2}a)]
71	374	60	53	-33	20
72	227	60	32	29	60
73	440	60	49	49	98
74	290	60	48	-16	32
75	221	60	43	25	67
76	306	60	38	39	78
77	249	60	37	-21	16
78	314	60	34	26	60
79	1206	60	37	7	44
80	1087	60	34	37	71
81	1056	60	44	49	93

The deviation and mean values of photovoltaic peak power and area of solar thermal collectors (STC) per heated areas based on Table 3 and sorted by the Net ZEB balance concept are shown in Fig. 8. Generally, buildings without a heat pump (HP) have larger solar thermal collectors and PV panels than buildings with heat pump. Also, buildings with Net ZEB balance have larger solar thermal collectors and higher installed nominal power (kWp) for PV panels than buildings with Net ZEB_L balance.

In case studies with Net ZEB_L balance, installation of a heat pump enables a mean reduction of solar thermal collectors by 50%. Installed nominal power (kWp) for PV panels are roughly the same. None of the Net ZEB balance buildings have heat pump.

Assuming that the buildings are equal to low energy/Passive House standard, taking the step from a low energy house/Passive House to a Net ZEB_L acquires instalment of 0.019 kWp PV panels and 0.030 m^2 of solar thermal collectors per gross heated floor area. Alternatively; 0.020 kWp for PV panels, 0.015 m^2 of solar thermal collectors and a heat pump.

Comparing cases without heat pump; taking the step from Net ZEB_L to Net ZEB acquires a mean increase of PV panels by 0.018 kWp and solar thermal collectors by 0.050 m^2 per gross heated floor area. This roughly corresponds to, taking the step from Net ZEB_L to Net ZEB, a doubled kWp installed for PV panels. The ratio of solar thermal collector area, comparing Net ZEB and Net ZEB_L, are eight to three.

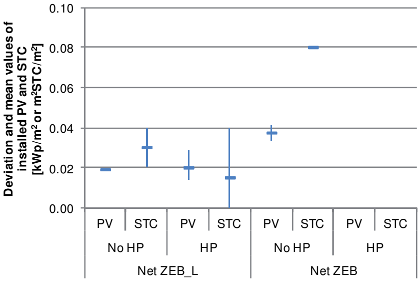

Fig. 8 PV and ST, sorted by type of Zero-balance concept and with/without installed HP. Distribution of PV and ST per heated floor area.

The average installed PV power, kWp/m^2, for Net ZEBs corresponds well with [12], which provides more in-depth analysis of Net ZEB characteristics. More detailed analyses of the characteristics of Net ZEBs may also be found in [3, 4].

3.3.2 Energy Payback Time and Net Energy Ratio

Energy Payback Time (EPT) and Net Energy Ratio (NER) were calculated according to Equation 3 and Equation 4. In order to calculate EPT and NER, ΔOE needs to be calculated. The calculations are based on non-renewable primary energy.

The results differ depending on the energy source replaced. E.g. if solar thermal collectors are replacing 1 kWh of electricity; ΔOE=2.52 kWh, replacing 1 kWh of district heating; ΔOE=0.79 kWh etc.

To compare the different energy supply strategies: district heating, electricity, oil or natural gas was compared with the photovoltaic, solar thermal or heat pump systems. The deviation and mean value of EPT and NER for all cases are presented in Table 4. Basis for the calculations is presented in Appendix B.

Heat pumps show by far the lowest EPT, often less than one year. The EPT for PV panels are often ten times higher, and for solar thermal collectors often three times higher. Hence, installing a heat pump is a recommended solution from a LCE perspective.

PV panels have the highest EPT and should therefore be the last option to consider. If, for any reason, the option of installing a heat pump is not chosen; the appropriate design strategy would be to first size and install a solar thermal collector system with respect to the energy needed for heating before considering PV. Furthermore, electricity generated from PV should not be used within the building to replace district heating; instead it should be exported to the grid, in order to replace electricity. However, this design strategy assumes that there is always an energy load in the grid. Furthermore it does not consider possible increased stress on the grid if an export strategy is chosen.

Examining the NER calculations, where high NER is preferable, confirms the recommendations above. However, some differences may be noted. Within the EPT comparison, there was roughly a factor three difference between PV panels and solar thermal collectors. Comparing NER, the difference is reduced; roughly to two. Comparing the heat pumps and solar thermal collectors, the mean factor difference of EPT is 3.8. The mean factor difference of NER is 5.8. The differences occur due to that the NER methodology includes the effect of the expected service life time of a measure. In this case the service life times are 30 years for PV panels and heat pumps, and 20 years for solar thermal collectors.

Table 4 Results from calculations of EPT and NER

Renewable energy supply option	Replacing energy source	Energy payback time [years]			Net energy ratio [-]		
		Max	Min	Mean	Max	Min	Mean
Photovoltaic	District heating	13.1	10.4	11.5	2.9	2.3	2.6
	Electricity	4.1	3.2	3.6	9.2	7.3	8.3
	Oil	7.7	6.1	6.8	5.0	3.9	4.5
	Natural gas	8.6	6.8	7.6	4.4	3.5	4.0
Solar thermal	District heating	4.7	2.6	3.8	7.6	4.3	5.4
	Electricity for heating	1.3	0.7	1.1	27.0	15.2	19.3
	Oil	2.7	1.5	2.2	13.0	7.3	9.3
	Natural gas	3.1	1.7	2.5	11.6	6.5	8.3
Heat pump	District heating	1.3	1.0	1.1	30.1	22.2	27.6
	Electricity for heating	0.4	0.3	0.3	106.6	78.8	92.8
	Oil	0.8	0.3	0.5	94.0	38.0	68.8
	Natural gas	0.9	0.3	0.5	94.0	33.8	66.3

3.3.3Distribution of embodied energy in Minergie-A projects

The distribution of embodied energy within the different Minergie-A cases are presented here. The results should be studied in the context that they are based on mid-European climate and primary energy factors for Swiss non-renewable primary energy factors [31].

The deviation of embodied energy in Minergie-A cases is shown in Fig. 9. Roughly 60 % of the embodied energy is due to the structural elements, 20 % for HVAC and 20 % for solar thermal collectors and PV panels. Heavy weight buildings do not necessarily have a higher embodied energy for structural elements. This could be a result of differences in expected life span for light and heavy weight constructions. Light weight walls have an expected life span of 40 years, heavy walls 60 years [29].

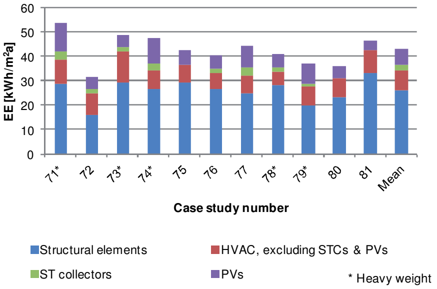

*Fig. 9 Embodied energy (EE) within Minergie-A cases (non-renewable primary energy). Cases marked with *; indicates heavy weight superstructure.*

The detailed distribution of embodied energy and operating energy use is presented in Fig. 10. For each project, demand and supply related to operating energy and embodied energy is presented. E.g. there is an energy demand to produce PV panels, presented as embodied energy on the demand side in Figure 10 (EE PVs). However, the PV panels also supply energy during building operation, presented as operating energy on the supply side (OE PVs).

Examining the demand for the different cases, the following rough division may be done: 35 % is embodied energy, 45 % is demand for plug loads and lighting and 20% is demand for heating, hot water and mechanical systems. The deviation of loads are roughly the same for buildings with Net ZEB_L balance and Net ZEB balance.

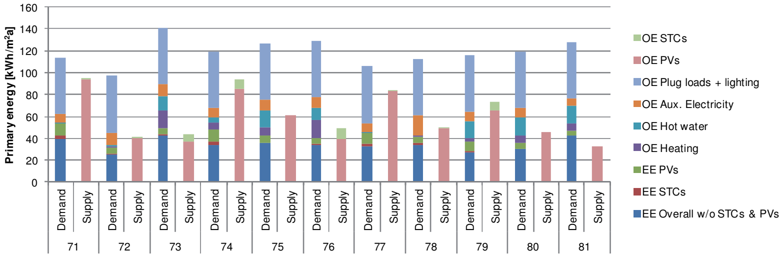

Fig. 10 Distribution of operating energy (OE) and embodied energy (EE) by demand and supply in Minergie-A projects (non-renewable primary energy).

Fig. 11 shows mean values of operating energy use and embodied energy for the three different building standards based on the 11 Minergie-A cases, recalculated as stated in chapter 2.2. Also the variation of the total life cycle energy use is presented.

The results show that the increase of embodied energy does not negatively affect the step from a low energy building towards a Net ZEB. When taking the step from a low energy building to a Net ZEB, the increase of embodied energy is about 25%. However, the operating energy use drops down to zero. The life cycle energy use of a Net ZEB is calculated to be about 40 % of the life cycle energy use a low energy building. The life cycle energy use of a Net ZEB is much lower compared to a low energy building.

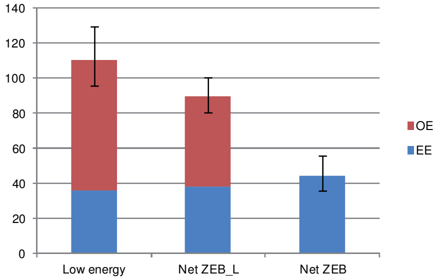

Fig. 11 Mean values of embodied energy (EE), operating energy (OE) and the variation of life cycle energy use (non-renewable primary energy), comparing three different building standards.

4. Conclusions

Since the oil crisis in the 1970s, efforts have been made to reduce energy use in buildings to reduce the oil dependency. Today, reduction of energy use in buildings is also seen as an important strategy for climate mitigation. As the operational energy (OE) is reduced, the relative share of embodied energy (EE) increases.

Worldwide, extensive work has been carried out or is in progress to identify and calculate the environmental impact from construction materials or assemblies. However, a mandatory national requirement for buildings is unlikely to be seen within the next few years. This is largely due to that it requires a large effort to collect, calculate and analyze the environmental impact of different materials. Furthermore, there is no standardized approach for data collection.

In the review of previous studies, five parameters have been identified which vary between the different studies and thus may influence the outcome; metric of evaluation, assumed life-span, boundary conditions, age of data and the origin of database. In order to increase transparency and allow for comparison between different studies, these parameters should always be clearly stated. In the review, it is possible to distinguish favoured choices within two of the parameters; life-span and metric of evaluation. The most used life span is 50 years and most studies choose consistently to apply primary energy for the LCE analysis.

The literature review shows that methods for calculating life cycle energy use are far from standardized. Today, it is therefore not suitable to try to include EE in a Net ZEB balance. However, it may be suitable to have as an additional/complementing requirement as defined within the Minergie-A requirements. To further facilitate the interpretation, clarification of results and increased transparency of analysis, the guidelines given in EN ISO 14040 [78] and EN ISO 14044 [79] may be followed.

Despite differences in different studies, the compilation shows that the previously found linear relationship between OE and LCE [19, 20] remains when the step is taken towards the Net ZEB balance.

Taking the step from Net ZEB_L to Net ZEB by increasing the use of solar energy roughly doubles the needed kWp of PV panels and more than doubles the area of solar thermal collectors. It is therefore imperative that all possible and cost efficient energy efficiency measures are applied in order to enable reaching the Net ZEB balance, especially in larger building where the relative areas suitable for PV panels and solar thermal collectors in relation to the heated area decreases. The analysis of EPT and NER for solar energy options shows that electricity from PV panels should primarily be used to replace electricity, not transformed and used for space heating or hot water heating.

The detailed analysis of the 11 Minergie-A buildings show that roughly 45 % of energy demand is due to plug loads and lighting and 35 % is embodied energy. The remaining energy loads are energy for heating, hot water and HVAC systems. The embodied energy is roughly to 60 % due to structural elements, 20 % due to HVAC systems and 20 % due to ST collectors and PV.

The embodied energy increases slightly when taking the step from a low-energy building towards Net ZEB balance. However, the energy savings achieved related to building operation OE exceeds, with great margin, the increased embodied energy. The overall assessment shows that the life cycle energy use of a Net ZEB is about

60% lower compared with the life cycle energy use of a low energy building/Passive House. From a life cycle energy perspective, the Net ZEB is preferable over a low energy building.

Today, structural elements hold the largest share of embodied energy in buildings. Therefore, a first step of implementing analysis of embodied energy could focus on structural elements. Technical systems that reduce the operating energy use, e.g. solar thermal collectors, PV panels and heat pumps, if properly designed; always reduce the operating energy use more than the increase of the embodied energy incorporated in the technical system.

The embodied energy has decreased slightly over time, indicating that the construction of buildings and technical systems in general has become more efficient over time. However, the relative share of embodied energy of the total life cycle energy is increasing. Increased use and acceptance of LCE analysis as an important parameter in the design of buildings may in a near future lead to design decisions not only based on energy savings related to operating energy. Thus, in new construction, choosing insulation material with low EE instead of increasing the amount of insulation in an already well-insulated construction may be a decision in a not so distant future.

5. Acknowledgements

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Appendix A

Table A.1 Summary of gathered non-residential case studies with LCE-analysis (Primary energy)

Case study	Size [m^2]	Lifespan	EE [kWh/m^{2}a]	OE [kWh/m^{2}a]	LCE [kWh/m^{2}a]	Reference
1	4400	50	38	258	296	[32]
2	4400	50	78	376	453	[32]
3	2151	80	30	70	100	[33]
4	4719	80	51	143	194	[34]
5	1700	50	67	56	123	[35]
6	1516	50	48	67	114	[4, 36]
7	11170	38	29	50	79	[37]
8	7300	75	28	1142	1170	[38]

Table A.2 Summary of gathered residential case studies with LCE-analysis (Primary energy)

Case study	Size [m^2]	Lifespan	EE [kWh/m^2a]	OE [kWh/m^2a]	LCE [kWh/m^2a]	Reference
9	236	50	34	206	240	[39]
10	91	50	57	208	265	[39]
11	135	50	39	317	356	[39]
12	155	50	52	310	362	[39]
13	132	50	58	236	294	[39]
14	163	50	46	172	218	[39]
15	120	50	55	255	309	[39]
16	140	50	46	403	449	[39]
17	239	50	54	195	250	[39]
18	211	50	66	187	252	[39]
19	140	50	36	185	221	[39]
20	130	50	61	192	253	[39]
21	154	50	41	211	252	[39]
22	120	50	55	322	377	[39]
23	147	50	63	168	231	[39]
24	170	50	56	188	244	[39]
25	120	50	91	241	332	[39]
26	320	50	47	200	247	[39]
27	121	50	48	305	353	[39]
28	164	50	61	327	388	[39]
29	122	50	61	189	250	[39]
30	305	50	40	111	151	[39]
31	168	50	52	202	254	[39]
32	192	50	60	166	227	[39]
33	124	50	95	417	512	[39]
34	200	50	20	44	64	[40]
35	200	50	17	46	63	[40]
36	200	50	16	51	66	[40]
37	200	50	19	49	67	[40]
38	200	50	14	77	91	[40]
39	108	50	61	163	223	[41]
40	45	60	26	15	40	[42]
41	228	50	37	353	390	[43]
42	228	50	41	115	157	[43]
43	1404	50	23	217	240	[44]
44	1404	50	54	217	271	[44]
45	1404	50	64	217	281	[44]
46	1404	50	16	228	245	[44]
47	1404	50	20	228	248	[44]
48	1404	50	26	228	255	[44]
49	1404	50	20	227	246	[44]
50	1404	50	23	227	250	[44]
51	1404	50	23	227	250	[44]
52	1453	50	31	131	163	[44]
53	1453	50	59	131	190	[44]
54	1453	50	51	131	182	[44]
55	1484	50	33	125	158	[44]
56	1484	50	48	125	172	[44]
57	1484	50	38	125	163	[44]
58	982	50	80	62	143	[44]
59	96	50	18	239	258	[45]
60	96	50	19	184	203	[45]
61	96	50	20	155	175	[45]
62	96	50	23	95	119	[45]
63	96	50	25	78	102	[45]
64	96	50	26	66	93	[45]

65	96	50	27	65	92	[45]
66	96	50	29	55	84	[45]
67	96	50	31	50	81	[45]
68	96	50	35	31	66	[45]
43	96	50	39	12	51	[45]
70	96	50	44	-7	37	[45]

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Appendix B

Table B.1 Effect on ΔEE_T and ΔEE in Minergie-A case studies due to PV and ST collectors

Case study	ΔEE_T *			ΔEE *			$-\Delta OE$**		
	[kWh/m^2 heated area]			[kWh/a, m^2 heated area]			[kWh/a, m^2 heated area]		
	PV	STC	HP	PV	STC	HP	PV	STC	HP
71	341	64		11.4	3.2		37.5	18.3	
72	153	33		5.1	1.6		15.9	10.2	
73	151	28	29	5.0	1.4	1.0	14.6	7.8	26.8
74	313	63		10.4	3.2		33.7	30.6	
75	198			6.6			24.1		
76	162	32	29	5.4	1.6	1.0	15.7	11.7	36.3
77	270	62		9.0	3.1		32.9	25.5	
78	161	32		5.4	1.6		19.6	8.7	
79	241	28		8.0	1.4		26.2	9.7	
80	160		29	5.3		1.0	18.2		34.7
81	118		29	3.9		1.0	12.9		35.5

* Non-renewable primary energy

** Un-weighted energy. Differences in primary energy are calculated using factors presented in Table 2

Articles VII

Net ZEB Office in Sweden - a case study, testing the Swedish Net ZEB definition

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Abstract

An important measure for climate change mitigation is reduction of energy use in buildings worldwide.

In 2010 Skanska Sverige AB began designing an office building in the southern parts of Sweden, aiming towards a Net Zero Energy Building (Net ZEB) balance. The construction work started in the middle of 2011.

In the beginning of 2012 Sveriges Centrum för Nollenergihus/the Swedish Centre for Zero-energy buildings (SCNH) published a Swedish definition for a zero-energy building in the Swedish climate. In short; the Swedish definition of a zero-energy building demands fulfilment of the passive house criteria, and that a zero energy balance must be reached over a year based on import/exported balance. This study summarises the overall design ideas, constructions, installations, energy balance of the office building and investigates whether the building reaches the zero energy-building definition according to SCNH. The simulations show that a Net ZEB balance may be reached. However, the passive house criterion is not reached. The study discusses pros and cons in the Swedish definition of "zero-energy building"/Net ZEB and suggests clarifications needed and possible amendment that may be implemented in an updated version of the definition.

1. Introduction

Reduction of energy use constitutes an important measure for climate change mitigation. Buildings today account for 40% of the world's primary energy use and 24% of the greenhouse gas emissions (International Energy Agency (IEA), 2011). The population and need for residential and non-residential buildings increases worldwide. Therefore, reduction of energy consumption and increased use of energy from renewable sources in the buildings sector constitute important measures required to reduce energy dependency and greenhouse gas emissions.

Today, the concept of Net Zero Energy Buildings (Net ZEBs) is no longer perceived as a concept that only can be reached in a very distant future. A growing number of projects in the world, in different climates, show that it is possible to reach Net ZEB balance with technologies available today on the market. Examples may be found in (Fachinformationszentrum, 2011; Lenoir, Garde, & Wurtz, 2011; Musall et al., 2010; SHC Task40/ECBCS Annex52 IEA, 2011; Voss & Musall, 2011).

In contradiction to autonomous Zero Energy Buildings (ZEBs), the Net ZEBs interacts with the energy infrastructure. Renewable energy generation covers the annual energy load. At a first glance, the "zero energy concept" seems simple and intuitive. However, there may be significant differences between definitions that seem similar. Relevant studies that investigate differences and try to clarify the definitions may be found in (BPIE, 2011; Kurnitski et al., 2011; A.J. Marszal et al., 2010; A. J. Marszal et al., 2011; Sartori et al., 2010; Sartori, Napolitano, & Voss, 2012). In the most recent of the studies (Sartori et al., 2012) a comprehensible framework is presented. The framework considers relevant aspects characterising Net ZEBs and may be used to define consistent (and comparable with others) Net ZEB definitions in accordance with country specific conditions. The presented framework was largely developed in the context of the joint IEA SHC Task40/ECBCS Annex52: Towards Net Zero Energy Solar Buildings (International Energy Agency (IEA) Solar Heating an Cooling programme (SHC) & (ECBCS), 2008).

In 2010, Skanska Sverige AB began designing an office building in the southern parts of Sweden, aiming towards Net ZEB balance, called "Väla Gård". The construction work started in the middle of 2011. The building was taken into use in the autumn of 2012. In the beginning of 2012 the Swedish Centre for Zero Energy Buildings (SCNH) published a revised definition of "mini energy house", passive house and zero-energy building (Sveriges Centrum för Nollenergihus, 2012) for the Swedish climate. In short; the Swedish definition of a zero-energy building demands the fulfilment of the Swedish passive house criteria, and that a weighted zero energy balance must be reached over a year based on import/export balance. Hence, it is a Net ZEB.

This study summarises the framework presented within the IEA SHC Task40/ECBCS Annex52 and the Swedish Net ZEB definition. Furthermore overall design ideas, constructions, installations and energy balance of the Net ZEB office are presented. The studied case investigates whether the building reaches the Net ZEB definition according to SCNH, discusses pros and cons in the Swedish definition of Net ZEB and proposes small clarifications and additions suggested for an updated version of the definition. The studied building is an office building. Hence, only the Swedish Net ZEB definition for non-residential buildings is addressed in this study.

1.1 Terminology and the balance concept of Net ZEB

In Figure 1 (left), the terminology used and the link between them is presented. The Net ZEB balance is reached when the weighted supply meets or exceeds the weighted demand. The general strategy to reach a Net ZEB balance may be described as a two-step procedure: first, apply energy efficiency measures to reduce energy demand (e.g. passive house design principle). Secondly, generate energy to achieve the balance, Figure 1(right).

The passive house design principle may be described as (Janson, 2010):

- Reducing thermal losses through the building and install/use a balanced ventilation system with a high system heat recovery efficiency.
- Minimize the need of electricity by installing energy efficient fans, pumps, appliances and lighting systems.
- Utilize solar energy, both for passive solar gains and as a source for domestic hot water production and local production of electricity.
- Measure and visualize the energy use in a user friendly and transparent way.

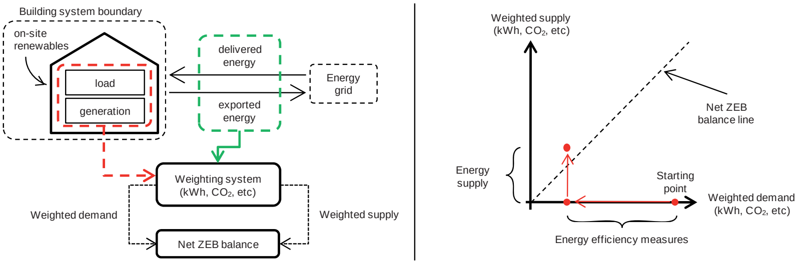


Figure 1 Based on (Sartori et al., 2012). Left; Sketch of connection between buildings and energy grids showing relevant terminology. Right; Graph representing the Net ZEB balance concept and strategy.

Different aspects, recommended to be addressed within the Net ZEB framework (Sartori et al., 2012) are summarised below:

1. *Building system boundary*
    1.1. *Physical boundary* - needed to know where to compare/measure energy flows in and out the system and to identify energy generated from renewable sources ”on-site”.
    1.2. *Balance boundary* - defines which energy uses that are included in the Net ZEB balance. The terminology described in EN 15603 [SIS 2008] may be used.
    1.3. *Boundary conditions* - represent definitions of reference climate, comfort standard and type of building use.
2. *Weighting system*
    2.1. *Metrics* - refers to the specific metric chosen for the Net ZEB balance. Common metrics are: primary energy (total or non renewable), site energy, carbon emissions, exergy, costs etc.
    2.2. *Symmetry* - demand and supply may be weighted symmetrically or asymmetrically. For example if costs are balanced, the tariffs may differ for export and import.
    2.3. *Time dependent accounting* - commonly static weighting factors are used. However quasi-static or dynamic weighting factors would most likely help the design of Net ZEBs towards more optimal interaction to the grid.
3. *Net ZEB balance*
    3.1. *Balancing period* - May differ, usually one year.
    3.2. *Type of balance* - refers to whether the balance is based on load/generation; the building’s energy demand compared to energy generation, no self-consumption evaluated, or import/export; energy flows to and from the building, passing the physical boundary. It shall be noted that the graphical presentation (Figure 1, right) of the two different balances will differ due to on-site energy self consumed and possible storage losses within the building if energy storage is used.
    3.3. *Energy efficiency* - in addition to the Net ZEB balance, requirements may be set on energy efficiency, such as U-values of windows, air tightness etc.

   3.4. *Energy supply* – there may be requirements on minimum share of the building's energy demand covered by renewable. Furthermore it may not be allowed to offset delivered electricity with exported heat, etc.

4. *Temporal energy match characteristics*
   4.1. *Load matching* - evaluations/requirements of/on- load matching may be set according to Equation 1.
   4.2. *Grid interaction* – evaluations/requirements of/on- grid matching may be set according to Equation 2 and Equation 3.
5. *Measurement and verification*

   In order to check that a building is in compliance with the definition, a procedure for calculations and/or measurements needs to be defined in order to verify the building.

$$f_{load,i,T} = \min[1, g_i/l_i] \qquad (1)$$

$$f_{grid,i,T} = (e_i\text{-}d_i)/\max[e_i\text{-}d_i] \qquad (2)$$

$$f_{grid,i,year,T} = \mathrm{STD}(f_{grid,i,T}) \qquad (3)$$

Where *g* is generation, *l* is load, e is exported energy, *d* is delivered energy, *i* is the energy carrier and *T* is the evaluation period, year, month, week, etc.

1.2 The Swedish Net ZEB definition

The Swedish Net ZEB definition (Sveriges Centrum för Nollenergihus, 2012) is presented below according to the framework presented above:

1. *Building system boundary*
   1.1. The *Physical boundary* is defined in accordance to the Swedish building regulations (Boverket, 2011). Hence, in general, the physical boundary is the building itself. However, the physical boundary is enhanced to the building site for solar thermal (ST) collectors, PV panels and equipment that generate heating or cooling (e.g. usually different types of heat pumps or biomass boilers). The Swedish building regulations are not clear regarding how to

account for wind mills and micro CHP plants on-site. However, the Swedish Net ZEB definition states that wind mills may be placed anywhere on the building site.

- 1.2. *Balance boundary* is also defined in accordance to the Swedish building regulations. Hence, energy used for heating, cooling and dehumidification, ventilation and humidification, hot water and permanently installed lighting of common spaces and utility rooms are included in the balance. Other services are not included in the balance (e.g. computers, copiers, TVs etc.).
- 1.3. *Boundary conditions* – The Swedish Net ZEB definition defines set point temperature for heating. Furthermore, it defines internal heat gains from occupancy presence and electricity use. Also energy use for heating of water is defined. Set point for cooling is not defined. No requirements or definitions are set for outdoor climate.

2. *Weighting system*
    - 2.1. The chosen *Metric* to calculate the Net ZEB balance is referred to as weighted energy.
    - 2.2. Symmetric weighting is applied.
    - 2.3. Static weighting factors are used. Hence, no *Time dependent accounting.* The following factors are used; $w_{electricity}$: 2.5, $w_{district\ heating}$: 0.8, $w_{district\ cooling}$: 0.4. All other energy carriers are multiplied by one, w_{other}: 0.4. (bio fuel, natural gas, oil etc.)
3. *Net ZEB balance*
    - 3.1. The *Balancing period* is one year.
    - 3.2. The *Type of balance* is import/export.
    - 3.3. *Energy efficiency* - in addition to the Net ZEB balance, the building must fulfil the Swedish passive house requirements, in short:
        - 3.3.1. Peak load for heating (VFT) $\leq 7.7 + 0.233 \cdot (21 - DVUT)$ W/m^2

          The maximum value may be increased for buildings with conditioned area (A_{temp}) < 400m^2 by 2 W/m^2 (*DVUT* is the design outdoor temperature)
        - 3.3.2. Air permeability, $q_{50} \leq 0.30$ l/s, m^2
        - 3.3.3. Average U-value for all windows and glazed areas ≤ 0.80 W/m^{2}K
    - 3.4. *Energy supply* – No requirements

4. *Temporal energy match characteristics*
    4.1. *Load matching* - No requirements.
    4.2. Grid interaction – No requirements.
5. *Measurement and verification*

    To enable verification of the energy performance, energy metering must be separated into heat and electricity. Electricity should also be separated into energy use included and excluded in the *Balance boundary*. Furthermore, consumption of hot water must be measured and operating hours for the building should be documented.

In addition to the requirements presented above, the Swedish Net ZEB definition requires:

1. Noise from ventilation system should not exceed sound class B, SS 025268 (Swedish Standards Insitute, 2007).
2. Indoor temperature must be investigated through simulations.
3. If the ventilation system is designed for intermittent operation, the design should ensure that air filters are dry before shut down.
4. Specific Fan Power and energy consumption for ventilation, pumps, lighting, motors, control, monitoring equipment etc. This must be reported together with the presentation of the energy simulation.
5. Electricity consumption and internal heat gains from these should be calculated, documented and compared with reference values, defined in the Net ZEB definition (the defined boundary conditions)
6. Material used for the construction should not have microbiological growth of abnormal quantity or have divergent odour. Isolated, visible, onset of mould growth on wood must be grounded or planed away.
    Wood is not allowed to have moisture content above 0.20 kg/kg when delivered on-site. Furthermore, it is not allowed to have moisture content above 0.16 kg/kg when interior and exterior cladding is mounted.

Critical moisture conditions for carpets, adhesives and fillers shall not be exceeded. Measurements shall be made by an authorized controller or equivalent.

2. Case study – Office Building; Väla Gård

2.1 Calculations and simulations

Calculations of U-values and thermal bridges are according to EN ISO 6946:2007 (Swedish Standards Institute, 2007a), EN ISO 13370:2007 (Swedish Standards Institute, 2007c) and EN ISO10211:2007 (Swedish Standards Institute, 2007b). All calculations are based on internal areas. To enable quick evaluation of different options, static calculations for maximum heat transfer losses and peak load for cooling is calculated. The calculation of maximum heat transfer losses is carried out according to the equation defined in the SCNH definition of Net ZEB. A simplified method for calculation of peak load for cooling (P_{Cool}), presented in Equation 4, was developed and used in this case study.

$$P_{Cool} = Q_{i,light} + Q_{i,eq} + Q_{Solar} \qquad (4)$$

Where $Q_{i,light}$ is internal heat gains due to electric light (W/m^2), $Q_{i,eq}$ is internal heat gains due to electric equipment (W/m^2) and Q_{Solar} is heat gains due to solar radiation calculated according to Equation 5 (W/m^2).

$$Q_{Solar} = (\Sigma A_g \cdot g_g \cdot Q_{solar,g})/A_{temp} \qquad (5)$$

Where A_g is the area of glazing (m^2), g_g is g-value of glazing (%), $Q_{solar,g}$ is intensity of solar radiation on window surface according to Equation 6 (W) and A_{temp} is conditioned area (m^2).
By using the solar height, S_h, at July 15th, the intensity of the solar radiation is calculated for different directions according to Equation 6 and presented in Figure 2 for different overhang angles.

$$Q_{Solar,g} = F_{dir} \cdot R_{dir} + F_{dif} \cdot R_{dif,sky} + R_{dif,ground} \qquad (6)$$

Where F_{dir} is shading correction factor for direct radiation (-), R_{dir} is direct radiation from the sun (W) (assumed to be $800 \cdot cos\ (S_h)$), F_{dif} is shading correction factor for diffuse radiation (-), $R_{dif,sky}$ is diffuse radiation from the sky (W) (assumed to be 100) and $R_{dif,ground}$ is diffuse radiation due to ground reflectance (W) (assumed to be 100).

If external screens are used, shading correction factors may be given by the manufactures or the suppliers. If fixed overhangs are used, shading correction factors may be calculated according to Equation 7 and Equation 8. Maximum solar radiation is calculated by checking different azimuths/directions of the sun, perpendicular to the different facades.

$$F_{dir} = \max[0, 1 - (0.5 \tan(\alpha)/\tan(90 - S_h))] \quad (7)$$

$$\mathrm{Fdif} = 1 - (\alpha/90) \quad (8)$$

Where α is the overhang angle as defined in Figure 2 (°) and S_h is solar height (°).

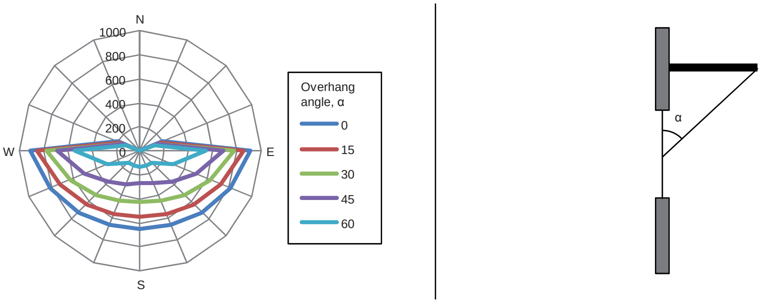


Figure 2 Left; $Q_{solar,g}$ *in different directions, sorted on different overhang angles. Right; Sketch describing the overhang angle.*

In addition to static calculations, simulations are carried out using IDA ICA 4.5 Beta (EQUA, 2012). Time-step for evaluation of import and export of energy was 15 minutes.

2.2 Description of case study

The studied building is a two-story office building situated in the south of Sweden. The overall design concept may be described as two main buildings with double pitched roofs, connected by a smaller building with a flat roof. The smaller building serves as an entrance and reception. On the first floor, the facade facing south west is shaded by a fixed overhang, $\alpha = 60°$. The gable walls on the “main buildings have fixed screens as solar shading, shading factor $F_{All} = 0.5$. The smaller “entrance building” has glass facades. The glazing on the upper floor has a fixed overhang shading, $\alpha = 75°$. The building has a geothermal heat pump system, with four heat pumps located at the building site. The heat pumps have variable speed compressors, enabling the system to adjust the speeds (and heat production) depending on the varying heating loads. Hence, the system eliminates energy losses caused by stopping and starting. Furthermore this enables the heat pumps to manage more than 100% of the estimated peak load. Free cooling is extracted from the bore holes during summer. Roof sides facing south west are equipped with PV panels. During summer, the PV panels are expected to export electricity to the grid. Input data for simulations and characteristics are presented in Figure 3, Figure 4, Figure 5, Table 1 and Table 2.

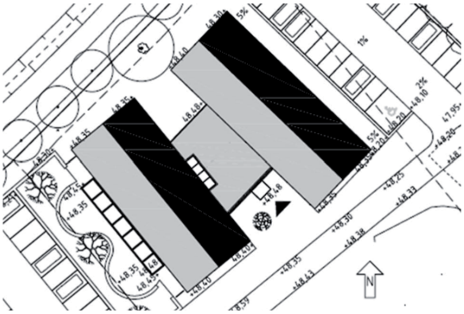


Figure 3 Orientation of building.

Figure 4 Facade facing south east.

Figure 5 Photograph of the building, as built, taken from west facing towards east.

Table 1 Input data for simulations – Constructions.

Constructions	
Slab on ground, 350 mm EPS	U=0.08 W/m^{2}K
Exterior walls, 200 mm Graphite EPS + 95 mm min. wool	U_c=0.11 W/m^{2}K
Double pitched roof, 520 mm min.wool	U_c=0.08 W/m^{2}K
Flat roof, 350 mm EPS + 20 mm min.wool	U_c=0.10 W/m^{2}K
Windows	U_w=0.90 W/m^{2}K
Glazed entrance	U_w=1.00 W/m^{2}K
Thermal bridges	To be identified
Air permeability (q_{50}/n_{50})	0.3 l/s, m^2 1.0 h^{-1}

Table 2 Input data for simulations - HVAC, Equipment, Solar energy.

HVAC, Equipment, Solar energy	
Heating and Cooling	Set point for temperature; 21-23 °C
Ventilation	VAV ventilation 1-8 l/s, m^2 Heat exchange efficiency; 82% Ventilation operating weekdays 6-18 (Ventilation off; July and Christmas)
Lighting and Equipement	Lighting (on/off); 6.7/0.1 W/m^2 Operating weekdays 7-17, off; July and Christmas Equipment (on/off); 6.7/0.1 W/m^2 operating weekdays 7-17, off; July and Christmas
Occopancy	Occupancy load; 0.05 occ/m^2 weekdays 7-17
Heat pump	$COP_{Heating}$; 3 $COP_{Cooling}$; 20
Solar energy	PV_{Area}; 450 m^2, kWp_{PV}; 67.5

In addition to the base case, calculations and simulations for other options, described in Table 3, are investigated.

Table 3 Different options as basis for calculations and simulations.

Name	**Description**
Base Case	As described in Figure 3
Opt. 1	Windows and glazing, U_w; 0.80 W/m^{2}K
Opt. 2	Solar shading all windows and glazing, fixed overhang; α=30°
Opt. 3	Solar shading all windows and glazing, fixed overhang; α=45°
Opt. 4	Solar shading all windows and glazing, fixed overhang; α=60°
Opt. 5	Air permeability (q_{50}/n_{50}); 0.15 l/s, m^2 / 0.5 h^{-1}
Opt. 6	Heat exchange efficiency; 90%
Opt. 7	All building elements, excluding windows and glazing; 0.11 W/m^{2}K including thermal bridges
Opt. 8	Opt. 1, 4, 5, 6 and 7

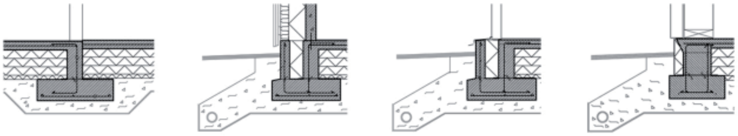
3. Results

Examining the construction design, sixteen potential thermal bridges were identified and calculated. All specific values for thermal bridges were increased by 10%, as input data for simulation, to account for any additional thermal bridges not identified (safety margin). The thermal bridges are presented in Figure 6. The thermal bridges increase the transmission heat transfer losses by 29%. In Figure 7, the relative impact of each identified thermal bridge is presented. The relative impact is calculated by multiplying the specific value of each thermal bridge with the specific quantity. As can be seen, roughly 50% of the transmission heat transfer losses through thermal bridges occur in junctions to the floor slab. A rather large share of the transmission heat transfer losses through thermal bridges also occur in junctions to windows.

To enable comparison of the static calculations and the dynamic simulations, the results from the calculations and simulations of peak loads for heating and cooling are presented together in Figure 8 (left). Also, the Net ZEB balances for the different options are presented (right).

Examining peak loads for heating and cooling, there are differences between the calculated and simulated results. Regarding peak load for heating, the simulations show a slightly higher peak load compared to the calculated value. This is likely due to that the lowest outdoor temperature in the simulation (-11.1°C) is lower compared to the calculated design temperature for heating (-9.2°C). The largest percentage difference within peak load for heating is within option 6, where the heat exchange efficiency is increased. This could be due to that the peak loads appear at night when the ventilation is off, which affects the simulation but not the static calculation. Over all, comparing static calculations and simulations regarding peak load for heating, show rather small percentage differences; 1-11%. There are bigger differences comparing peak loads for cooling; 11-34%. The biggest differences are in options where large external overhangs are considered, option 4 and option 8. The percentage differences are 29 % and 34 % respectively. In all other options, percentage differences vary between 11% and 17%. A better convergence may be reached by adjusting the simplified model, choosing a later day of the year to calculate the solar height and adjusting assumed intensity of the solar radiation.

The building as built, and all investigated options, outperforms the Net ZEB balance (Figure 8, right). Examining the import export/balance for the different options in Figure 8, it is hard to distinguish differences between the different options. This is due to the geothermal heat pumps which reduce the effects of the different investigated options. The effects of the different options are somewhat larger when investigating load/generation balance in the same figure.

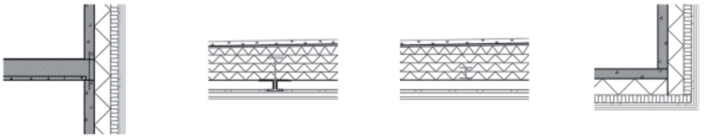


Floor slab – Load bearing inner wall. Ψi=0.281 W/mK

Floor slab – External load bearing wall. Ψi=0.382 W/mK

Floor slab – Windows/window doors. Ψi=0.382 W/mK

Floor slab – Glazed facade. Ψi=0.525 W/mK

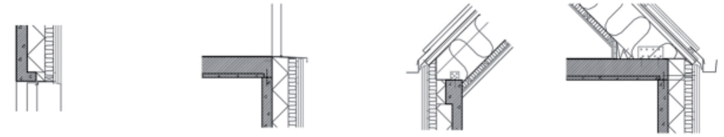


Intermediate floor – External wall. Ψi=0.029 W/mK

Recessed steel beam in roof. (Large) Ψi=0.071 W/mK

Recessed steel beam in roof. (Small) Ψi=0.016 W/mK

Exterior corner. Ψi=0.043 W/mK

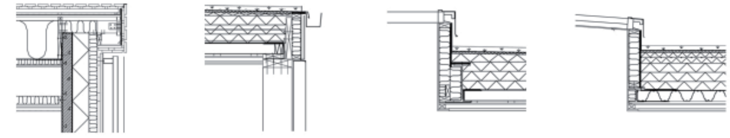


External wall – Window. Ψi=0.063 W/mK

Intermediate floor – Window. Ψi=0.052 W/mK

External wall – Roof, long side. (1) Ψi=0.091 W/mK

External wall – Roof, long side. (2) Ψi=0.178 W/mK



External wall – Roof, gable side. Ψi=0.095 W/mK

Glazed facade – Roof. Ψi=0.105 W/mK

Roof – Window 1. Ψi=0.219 W/mK

Roof – Window 2. Ψi=0.218 W/mK

Figure 6 Identified thermal bridges. Presented values do not include any safety margin

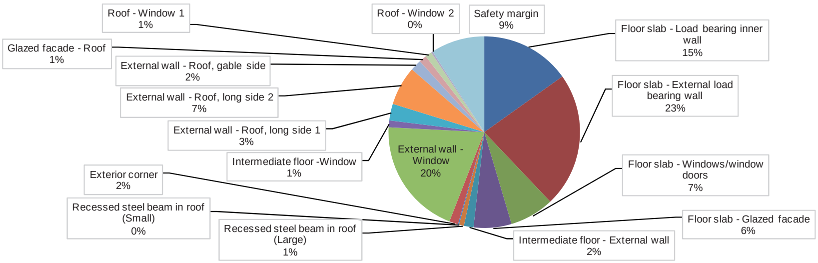


Figure 7 Relative impact of indentified thermal bridges

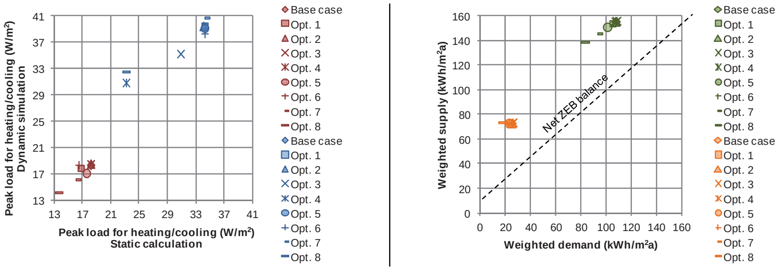


Figure 8 Left; Peak load for heating (red, lower left in figure) and cooling (blue, upper right in figure), static calculations vs. dynamic simulations. Right; Weighted supply and weighted demand. Import/export balance (orange, lower left) and load/generation balance (green, upper right) are presented

There are no disparities between the difference between load - generation and import - export for each investigated option. This is due to that the simulations did not include modelling of hot water storage tanks. It is assumed that the consumption of electric energy for heat pumps simply is the heat- and cooling loads divided by the specific COPs assumed for the system. More detailed modelling of the heat pumps and the hot water storage tanks would result in disparities.

4. Discussions and conclusions

Since this office was designed before there was a Swedish definition of Net ZEB; is it not surprising that all requirements within the Swedish Net ZEB definition are not fulfilled. However, this study shows that it is possible to reach the most important requirement in the Swedish Net ZEB definition, i.e. the Net ZEB balance, using existing technologies. The office building, as built, theoretically reaches the Net ZEB balance but does not fulfil the energy efficiency requirement regarding peak load for heating and U-values for windows set in the Swedish Net ZEB definition. To reach the requirement regarding peak load for heating all investigated options would have been needed to include.

A large share of the transmission heat transfer losses occur through thermal bridges (29%). This may be perceived as if the building has large thermal bridges. This is not the case. The thermal bridges accounts for a relatively large share primarily due to that all building elements have a high heat resistance. However, thermal bridges occurring in junctions related to the floor slab and windows could have been better designed. The footings around the floor slab perimeter and underneath the interior load bearing walls could have been fitted with insulation on the exterior side. The reason for not mounting insulation around the footings is most likely due to structural design; the risk of settling is low when no insulation is used. However, there are insulation products on the market that may handle/carry large loads, e.g. Foamglas® (Foamglas, 2013) and XPS, extruded polystyrene boards, (Sundolitt, 2013). The specific value of the thermal bridge due to window embrasures is relatively low. The high relative impact is due to the large quantity. So even if the specific value is low some extra attention should have been given to the junction between external wall and window. The thickening of the interior concrete construction could probably be reduced in order to further reduce the thermal bridge.

Examining the impact of the different options; three options have a slightly larger impact on the energy demand of building. Hence, the following recommendations could be given if the building still was in the design phase, or was to be redesigned:

- Investigate whether it is feasible to further improve the heat resistance of building elements. I.e. Investigated option 7; all building elements, excluding windows and glazing; 0.11 W/m^{2}K including thermal bridges, reduced the energy demand by 13 %.
- Try to improve the air tightness. Make sure to carry out early air tightness tests, to identify potential improvements, and to test the building as built.

I.e. Investigated option 5; air permeability (q_{50}/n_{50}) 0.15 l/s, m^2 / 0.5 $^{h-1}$, reduced the energy demand by 6 %.

- Investigate if it is possible to install windows with lower U-value.
  I.e. Investigated option 1; windows and glazed entrance, Uw; 0.80 W/m^2K, reduced the energy demand by 2%.

It shall be noted that the Swedish Net ZEB definition excludes energy used for plug loads. To ensure low costs related to energy use during operation; all measures that may reduce the use of electricity should be investigated.

After testing the Swedish Net ZEB definitions some points may be made. The *Physical boundary* is rather clear. To further enhance the clearness, the definition could refer to the building site as the physical boundary, if that is what is intended, instead of referring to the Swedish building regulations. The *Balance boundary* is also rather clear. A complementary reference to the Swedish building regulations could be the reports published by SVEBY (SVEBY, 2011), which clarify and interpret the Swedish building regulations. E.g. the Swedish building regulations do not specifically give guidance regarding whether energy for elevators are included in the balance boundary, but SVEBY does. Regarding *Boundary conditions*; the design temperatures which shall be used to calculate the peak load for heating are well defined. Input data for simulations could be further clarified, both regarding interior and exterior boundary conditions. However, there are many factors affecting the result of an energy simulation. It may be more suitable to specify a report template or to develop a simple tool to verify the energy performance. Preferably it could be an upgrade of the existing tool; Energihuskalkyl (Aton Teknikkonsult AB, 2009).

The Net ZEB definition uses the terms import and export on a yearly basis. Hence there is no actual need to clarify the *Type of balance.* However, since there are no defined input data in short time steps, it may be more suitable to use load/generation balance. I.e. the annual energy needed and the annual energy generated.

If load/generation balance is introduced there may be a need to specify how to calculate/consider on-site generation that does not have the ability to export excess energy, e.g. solar thermal collectors producing heat for domestic hot water.

There are today no requirements regarding *Temporal energy match characteristics.* A future update of the Swedish Net ZEB definition may include these. If these should be included, further studies should be made in collaboration with stakeholders representing the Nordic energy infrastructure. As an alternative to *Temporal energy match characteristics* quasi-static or dynamic weighting factors could be used.

This study also presents a simplified method for calculations of peak loads for cooling. The method could be improved and used as a method to estimate peak loads for cooling in early design phases.

The Swedish Net ZEB definition was not available when this building was designed and constructed. All investigated options would have been able to implement except for the requirement on U-values for windows and glazing. To be able to meet that specific requirement, changes in the architectural design would have been required. From a design perspective it is always important to consider measures for energy efficiency before aiming at a Net ZEB Balance. Net ZEB office buildings may not need the same requirements on energy efficiency as residential buildings due to the rather high internal heat gains. The energy efficiency is likely to be optimized anyway due to market principles: it is very costly to construct a Net ZEB that is not first of all an energy efficient building.

5. Acknowledgements

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The building will be assessed during the operational phase, 2012-2014, in order to verify simulations and to assess the indoor environment. The measurements are to a large extent financed by LÅGAN (LÅGAN, 2013).

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Articles VIII

Calculation of thermal bridges in (Nordic) building envelopes – risk of performance failure due to inconsistent use of methodology

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Abstract

Reduction of energy use in buildings is an important measure to achieve climate change mitigation. It is essential to minimize heat losses when designing and building energy efficient buildings. For an energy-efficient building in a cold climate, a large part of the space heating demand is caused by transmission losses through the building envelope. Therefore, calculations of these must be carried out in a correct way to ensure a properly sized heating system and a good indoor climate. There is today a risk of misunderstanding and inconsistent use of methodology when transmission heat transfer is calculated. To investigate the state of knowledge among Swedish consultants a survey was conducted regarding thermal bridges and calculations of transmission heat transfer. Furthermore, the impact of thermal bridges was studied by comparative calculations for a case study building with different building systems and different amounts of insulation. The study shows that the relevant standards and the building code in Sweden are interpreted in many different ways regarding calculation of transmission heat transfer and energy performance. There is a lack of understanding regarding the impact of different measuring methods on thermal bridges. When more insulation is used the relative impact of thermal bridges increases. It is therefore not suitable to use a single predefined percentage factor, increasing the transmission heat transfer through building elements, to account for the effect of thermal bridges. If values for

normalized thermal bridges are to be used, they need to be differentiated by building system and different amounts of insulation.

Highlights

> The effect of different measuring methods to define building elements is addressed > The state of knowledge regarding calculation of transmission heat transfer is investigated > The increasing importance of correct calculations of thermal bridges is shown

Keywords

Thermal bridges, EN ISO 13789, EN ISO 10211, transmission heat transfer, dimensions

1. Introduction

Buildings account for 40% of the primary energy use and 24% of the generation of green house gases worldwide [1]. The population of the world, and consequently also the building sector, is expanding. Therefore, a reduction of the specific energy demand of buildings and increased use of renewable energy are important measures of climate change mitigation.

To promote improvement of energy performance within the European Union, the members of the European Parliament approved the directive 2002/91/EC on Energy Performance of Buildings, EPBD [2], in December 2002. On the 18th of May 2010 a recast of the EPBD was approved [3] which further clarifies the intention that buildings shall have a low energy demand. The recast of the EPBD specifies that by the end of 2020 all new buildings shall be “nearly zero-energy buildings”. A nearly zero-energy building is defined as a building with a very high energy performance and the low amount of energy required should be covered to a very significant extent by energy from renewable sources.

Several stakeholders are already today making efforts to design and build buildings that outperform the Swedish building code on energy performance requirements. The share of new dwellings designed as passive houses or low energy buildings has increased noticeably in Sweden. The share in the residential sector has increased from 0.7% in 2008 to 7.2% in 2010. For multi dwelling buildings, the share is even higher, 11.2 % in 2010 [4].

To design and build energy efficient buildings, different design strategies may be applied such as the Energy triangle, The Kyoto Pyramid Passive energy design process, The IBC Energy Design Pyramid [5] or the Passive house design principle [6]. They differ slightly from each other, but the common first fundamental step is to reduce the energy demand, which in a Nordic climate is achieved by constructing a well insulated and air tight building envelope in combination with balanced ventilation with high system heat recovery efficiency.

When a building is designed according to such principles, most of the energy demand for space heating is caused by transmission heat transfer through building elements and thermal bridges. It is therefore vital to calculate the transmission heat transfer in a correct way and not exclude or misjudge what may be a potential thermal bridge. Poor calculations may lead to undersized heating systems, poor indoor climate and energy costs that exceed expectations. By extension, it is likely that this could lead to economical consequences for the builder, the client and/or the consultants.

This article consistently uses the term; transmission heat transfer, in order to distinguish transmission heat transfer from ventilation heat transfer. These terms are derived from EN ISO 13789 [7].

The EPBD states that the energy performance of buildings should be calculated on the basis of a methodology, which takes into account existing European standards. A commonly used standard to calculate the transmission heat transfer coefficient is EN ISO 13789, which is referred to in most Nordic countries directly or indirectly, e.g. in Denmark [8], Finland [9], Norway [10] and Sweden [11]. To calculate the transmission heat transfer coefficients, the building envelope needs to be clearly defined and divided into different building elements.

The dimension of the building elements can be measured according to three different methods which differ in the way of whether the junctions between different elements are included or excluded in the areas of these elements. Different stakeholders may apply the standard differently; thus there is a risk of misunderstanding.

An additional risk of misunderstanding is that different, usually simplified, methods may be used in order to account for thermal transmittance through thermal bridges [12]. E.g. in the Norwegian standard for calculation of energy performance of buildings, NS 3031 [13], three different normalized thermal bridges values relative to the heated floor area are specified. These values are differentiated based on whether the building has a wooden construction or not and the amount of insulation used to decrease the thermal bridges in the exterior parts of the wall constructions. In Sweden, the impact of thermal bridges may be accounted for by increasing calculated transmission heat transfer through building elements by 20%, regardless of building system used [14]. In Denmark, typical solutions are covered by tabulated values [15]. In Finland, a simplified method is used where the effect of thermal bridges usually are included in the calculated transmission heat transfer through building elements by weighting thermal conductivity of different materials [16]. Calculations and realisation of details are not controlled by any authorities [12]. In Germany, thermal bridges are taken into account by increasing the calculated transmission heat transfer by 0.10 W/m^2K. However, this increase may be reduced by 50% if junctions between different building elements are designed according to best practice examples, given by the national standard [17].

Simplified methods, not taking into account effects of different construction methods or quantities of insulation, may be incorrect. A previous investigation has indicated that the transmission heat transfer losses due to thermal bridges may increase when more insulation is used in exterior walls [18]. Furthermore, it indicates that the relative increase of the transmission heat transfer through building elements that is needed to account for thermal bridges increases with increased insulation thickness. The increasing importance of thermal bridges are probably the highest in the North European countries since the standard amounts of insulation applied in buildings today are high compared to other European countries [19-24].

The subject, thermal bridges; is not new. There are several studies that have investigated transmission heat transfer losses, through building envelopes including thermal bridges [25-42]. Most of the studies investigate the effect of different calculation and simulation methodologies, such as static/dynamic and 1D/2D/3D [25-31]. Many studies also investigate the impact of thermal bridges may have on transmission heat transfer losses, through building envelopes [32-37]. Some studies mainly focus on cost-efficient or cost-optimal quantities of insulation [39-42]. As mentioned earlier, different measuring methods may be used to quantify building elements. Of the previous studies mentioned above; only two studies clearly defines how they quantify building elements [37, 41]. Furthermore, all studies on cost-optimal/cost-efficient quantities handle thermal bridges using simplified methods. I.e. the results of optimal quantities may be incorrect.

This article presents the state of knowledge regarding thermal bridges among Swedish engineers and architects in order to see if there is a risk of misunderstanding and therefore, need for guidelines. Furthermore, it shows the relative impact of thermal bridges in different building systems using different amounts of insulation. A survey among Swedish engineers and architects was carried out in combination with comparative calculations of thermal transmittance through building envelopes with different external wall constructions and insulation thickness.

2. Methodology

2.1Calculation of transmission heat transfer through building elements and thermal bridges

To calculate heat transmission through a building envelope, the transmission heat transfer coefficient H_T is calculated as in equation 1:

$$H_T = \Sigma_i A_i U_i + \Sigma_k l_k \Psi_k + \Sigma_j \chi_j + A_g U_g + P\Psi_g \qquad (1)$$

Where A_i is the area of the building element i adjacent to outdoor air, U_i is the thermal transmittance of the element i, l_k is the length of the thermal bridge k, Ψ_k is the linear thermal transmittance of the thermal bridge k, χ_j is the point thermal bridge j, A_g is the area of the ground construction, U_g is the thermal transmittance of the ground construction, P is the perimeter of the ground construction and Ψ_g is the linear thermal transmittance associated with wall-floor junction. Calculations of U-values follow EN ISO 6946 [43] and EN ISO 13370 [44].

Thermal bridges may be defined as a part of the building envelope penetrated by materials with different thermal conductivity and/or with changed thickness/amount of materials used and/or with difference between internal and external areas, according to EN ISO 10211 [45].

The linear thermal transmittance of the thermal bridges (Ψ) is calculated as in equation 2:

$$\Psi = L_{2D} - \Sigma_{(j=1)^\wedge(N\_j)} U_j l_j \qquad (2)$$

Where L_{2D} is the thermal coupling coefficient obtained from a 2-D calculation, U_j is the thermal transmittance of the 1-D element j and l_j is the length of the 1-D element j.

The point thermal transmittance of the thermal bridges (χ) is calculated as in equation 3:

$$\chi = L3D - \Sigma_{(i=1)^\wedge(N\_i)} U_i A_i - \Sigma_{(j=1)^\wedge(N\_j)} \Psi_j l_j \qquad (3)$$

Where L_{3D} is the thermal coupling coefficient obtained from a 3-D calculation, Ψ_j is the linear thermal transmittance calculated according to Equation 2 and l_j is the length of the thermal linear thermal bridge.

Measuring of lengths and areas may be done according to three different ways; internal, overall internal or external dimensions. The differences are shown in Fig. 1.

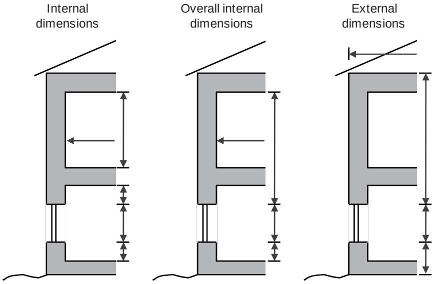

Fig. 1 Three different methods of measurement according to EN ISO 13789

Any of the measurement methods in Fig. 1 may be used. Specific values for linear thermal bridges and point thermal bridges vary depending on the measuring system used. To avoid misunderstandings and to enable comparisons, subscripts shown in Table 1 will be used in this study.

Table 1 Subscripts to clarify used system of measuring

Subscript	Definition
i	Internal dimensions
oi	Overall internal dimensions
e	External dimensions

2.2 The Survey

Recipients for the survey were gathered by contacting the major building engineering, architect and construction firms in Sweden, explaining that a short survey was to be conducted regarding handling of thermal bridges and energy calculations. If the company had employees who worked with assignments related to these questions, contact information in the form of e-mail address was collected. Through this method 100 engineers and architects were identified, who received an electronic questionnaire. Two reminders were sent out; in total 73 answers were received from 33 different firms/workplaces. The survey was conducted during September and October, 2010.

The questionnaire was based on three different sections. Initially, the questions addressed measuring methods used for quantification of areas. Subsequently the respondents were asked to review junctions, as shown in Fig. 2, and they were asked whether the junction increases transmission heat transfer in addition to the losses included in building elements or not. Finally, general questions were asked regarding professional background, work experience, approach used to assess thermal bridges, etc.

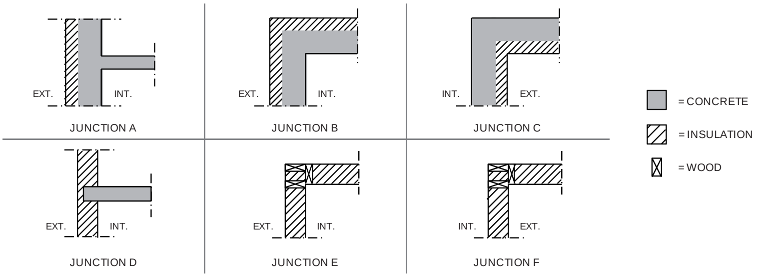

Fig. 2 Presentation of schematic/simplified junctions, included in the questionnaire. Internal environment is marked INT. External environment is marked EXT. Junction A & D are vertical sections, all other sections are horizontal sections.

2.3 Quantification of thermal bridges

To investigate the effect of thermal bridges, a small multi dwelling building with eight apartments was chosen as a case study. The building is a two floor residential building with four apartments on each floor. Different building envelopes and junctions were modelled with HEAT2.8 [46] and HEAT 3.6 [47]. Key features of the building and the investigated potential thermal bridges are shown in Fig. 3 and Table 2.

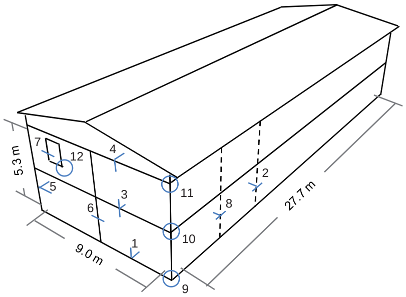

Fig. 3 Case study building

Table 2 Characteristics of reference building (measuring is based on internal dimensions). Junction number refers to Figure 3.

Characteristic	Data	Unit	Clarification
Heated area	498.0	m^2	As defined in the Swedish building regulations [11]
Windows/doors	72.5	m^2	
Junction 1	73.3	m	Ground floor slab – exterior wall
Junction 2	30.2	m	Interior load bearing wall – exterior wall
Junction 3	73.3	m	Interior floor slab – exterior wall
Junction 4	73.3	m	Attic floor slab – exterior wall
Junction 5	20.2	m	External wall corner
Junction 6	20.2	m	Connection of prefabricated wall elements
Junction 7	210.4	m	Exterior wall – window-/door frame
Junction 8	70.6	m	Exterior wall – internal non load bearing wall
Junction 9	4	pcs	External corner; floor slab – exterior wall
Junction 10	4	pcs	External corner; interior floor slab – exterior wall
Junction 11	4	pcs	External corner; attic floor slab – exterior wall
Junction 12	144	pcs	External corner; exterior wall – window-/door frame

Common building systems for exterior walls in Sweden were chosen; concrete walls with external insulation and cladding, precast concrete sandwich walls and insulated wooden frame wall constructions with cladding. The transmission heat transfer coefficient, H_T, was investigated for the three different building categories as shown in Table 3 for all three exterior wall systems. To investigate the differences between the measuring methods, Ψ_i, Ψ_{oi}, Ψ_e, have been calculated for each case and with areas for building elements quantified according to the three different measuring methods.

The U-values for the old building stock and for new buildings were collected from an extensive field study conducted by the Swedish National Board of Housing, Building and Planning, called BETSI [48], and the current energy performance requirements in the Swedish building code [11]. The U-values for best practice were taken from [6]. U-values specified for the old building stock are equivalent to buildings constructed before 1976. To achieve the required U-values, the amount of insulation was varied and different windows were modelled as shown in Fig. 4. In all combinations, accompanying structures as floor slab on ground, intermediate floor and roof construction, were concrete constructions.

Table 3 Different levels of U-values used

	U-value for different building categories (W/m^{2}K)		
Construction	Old building stock	New construction	Best practice
Floor slab on ground	0.31	0.17	0.09
Roof	0.20	0.12	0.08
External walls	0.35	0.20	0.09
Windows/ doors	2.30	1.50	0.90

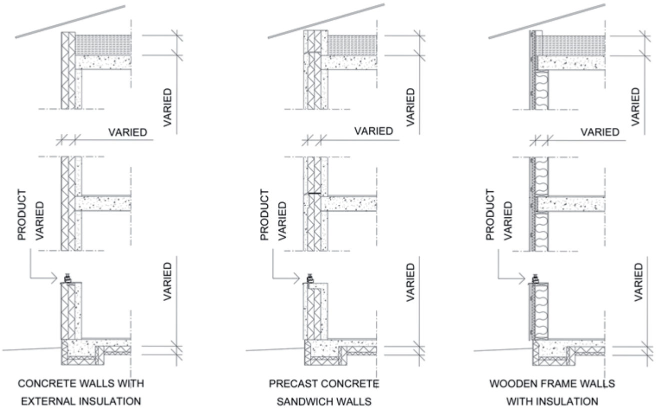

Fig. 4 Description of varied building systems and insulation thicknesses

3. Results

3.1 The Survey

The respondents had good knowledge of energy calculations; 84% (54 respondents) had work experience of energy calculations. Out of these 54 respondents, 63% had more than five years of work experience. This reflects the intention to find experienced professionals.

Internal measuring was most frequently used by the respondents to define building elements, and external measuring was mostly used to define a building's envelope area. However, the deviation of answers shows that there are no specific measuring method that can be assumed to be the norm in Sweden. The other predefined measuring methods were also used to an extent which exceeded 20% for each measuring method.

The results were slightly more uniform when the respondents were asked how they interpret the Swedish definition of building element area, A_i, and enclosing area, A_{om}. The area A_{om} is defined as "Total surface area of the enclosing parts of the building in contact with the heated indoor air (m^2)" according to the Swedish building regulations, BBR [11]. The result shows that internal measuring is the most common interpretation of the Swedish building regulations. Around half of the respondents replied that they interpreted the building regulations as that internal measuring should be applied. Roughly one third replied that overall internal measuring should be applied. A breakdown of the answers regarding the method of measurement is given in Table 4.

Table 4 Distribution of answers to questions 1-4

Question	Method of measurement				
	Internal	Overall internal	External	Other	No answer
Q1: Method of measurement used for quantification of building elements in energy calculations	42%	22%	29%	7%	0%
Q2: Method of measurement used to define a building's enclosing area	29%	22%	44%	1%	4%
Q3: Method of measurement used for quantities of A_i according to the Swedish definition in BBR	57%	29%	4%	0%	10%
Q4: Method of measurement used to define a building's A_{om} according to the Swedish definition in BBR	48%	36%	7%	0%	9%

The specific values for thermal bridges will vary depending on the chosen measuring method for the quantification of building elements, A_i, as stated in Section 2.1. The result from the assessment of junctions has therefore been sorted based on the chosen measuring method to quantify A_i, see Fig 5. For example; If a respondent answered that A_i is defined by internal measuring and afterwards answered that junction A, which is a thermal bridge only due to the difference between internal and external areas, is not a thermal bridge; The answer is incorrect and therefore listed as incorrect.

In the assessment of the first two junctions (A & B), which had a smaller internal area compared to the external areas, 53% and 52% of the respondents gave an incorrect answer to each question respectively. The third junction (C), which had a larger internal area compared to the external area, had a slightly lower percentage of incorrect answers; 39%. Junctions D & E were thermal bridges both due to the effect of partial penetration of the building envelope by materials with different thermal conductivity and differences between internal and external areas. The assessments from the respondents here showed a significantly lower incorrectness; 12% (D) and 8% (E) of the respondents made an incorrect assessment. The last junction, F, was a junction where the insulation was penetrated by wood which resulted in an increased thermal transmittance. However, the effect of the difference between internal and external area was larger. This junction had the largest amount of incorrect answers; 85%.

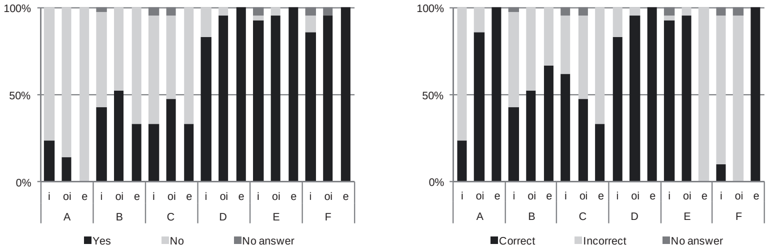

Fig. 5 Answers to the assessment of junctions A-F, sorted by chosen measuring method.
Left: Answers given by the respondents to the question: will this junction increase the transmission heat transfer losses in addition to the losses included in building elements? Right: Correct and incorrect answers

The respondents who interpreted quantification of A_i as internal measuring had a slightly higher share of incorrect answers (45%) compared to respondents who interpreted that A_i should be based on the overall internal (36%) or external (33%) measuring. The breakdown is presented in Table 5.

Table 5 Number of answers in the assessment of junctions based on correct, incorrect and N/A

Method of measurement	Allocation of answers		
	Correct answers	Incorrect answers	N/A
Internal	132	113	7
Overall internal	79	45	2
External	12	6	0
Total	223	164	9

The most common method used by the respondents to account for thermal bridges was to quantify the amount of thermal bridges and multiply the quantities with default values from literature or energy calculation software (44%). The second most common method (22%) was to increase the thermal transmittance of building elements (including all elements; walls, roof, windows, etc.) by a certain percentage. The used percentage factor varied between 5% and 20%, median; 15%.

3.2 Influence of thermal bridges on the case study building

The calculated transmission heat transfer coefficient, H_T, for the case study building (Fig. 3), based on different measuring methods, different building systems for exterior walls and different building categories is presented in Fig. 6. The total transmission heat transfer coefficient is the same, regardless of measuring method used, within each specific wall constructions in each building category. E.g. a building designed with exterior concrete walls according to best practice has the same H_T regardless of measuring method. However, the share of transmission heat transfer due to thermal bridges varies. The share of transmission heat transfer due to thermal bridges is the highest in the best practice building category for all three building systems. The share of thermal bridges is always the highest if internal measuring is used, regardless of exterior wall construction and building category.

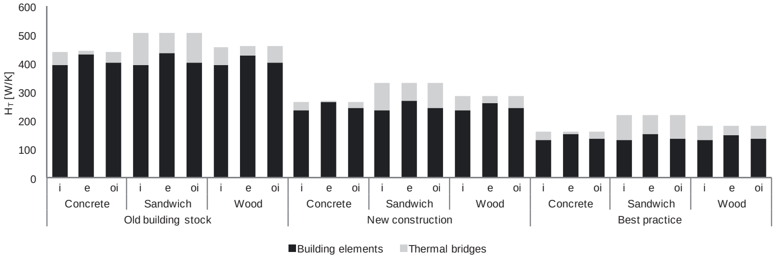

Fig. 6 Calculated transmission heat transfer coefficient, H_T, by different measuring method, exterior wall constructions and building categories.

The share of transmission heat transfer losses due to the thermal bridges is presented in Table 6. In the cases where external walls are concrete walls with external insulation, the share varies between 2% and 17%. The share varies between 7% and 27% in wooden frame walls with insulation. The highest shares, between 14% and

39%, are found in cases with precast concrete sandwich walls. The corresponding increase in percentage factor, which should be used if one is only increasing the transmission heat transfer coefficient by a certain percentage instead of analysing thermal bridges, is consequently even higher. In the worst case, the corresponding increase is 64 %. This applies to precast sandwich walls and insulation thickness equivalent to best practice.

Table 6 The share of the transmission heat transfer coefficient, HT, due to thermal bridges by different measuring methods, building system and building category

Measuring method	Exterior wall constructions	Building categories		
		Old building stock	New Construction	Best practice
Internal	Concrete walls with external insulation	11%	11%	17%
	Precast concrete sandwich walls	22%	28%	39%
	Wood stud walls with insulation	14%	17%	27%
Overall internal	Concrete walls with external insulation	8%	9%	15%
	Precast concrete sandwich walls	20%	26%	38%
	Wood stud walls with insulation	12%	15%	26%
External	Concrete walls with external insulation	3%	2%	6%
	Precast concrete sandwich walls	14%	19%	31%
	Wood stud walls with insulation	7%	9%	18%

The transmission heat transfer losses due to thermal bridges have been summarized by multiplying the specific values for each thermal bridge with the corresponding quantity for the case study building (Fig. 3). The summation has been done based on the three different measuring methods and the various U-values as defined in Table 3. The distribution of transmission heat transfer losses due to thermal bridges is shown in Fig. 7.

The precast concrete wall system shows a decrease of transmission heat transfer losses due to thermal bridges when more insulation is added, regardless of measuring method applied. However, the transmission heat transfer losses are very high in all cases.

Comparing the old building stock and new construction, the transmission heat transfer through thermal bridges is lower in new constructions. This is true regardless of exterior wall construction.

However, almost no change or a small increase of the transmission heat transfer losses due to thermal bridges can be seen when the step is taken from the building category of new construction to the best practice. This is due to that the specific value of some thermal bridges increases when more insulation is used.

In many junctions, the specific value of thermal bridges decreases or barely changes when more insulation is used. However, some junctions show a significant increase in transmission heat transfer. Regardless of the building system for the external walls, the specific value for the junction between the floor slab and external wall (J1) is increasing. Within the building system with precast concrete sandwich walls, the specific value of the thermal bridge between external wall and window-/door frame is also increasing (J7) when more insulation is used. Within the building system with wooden framework, more junctions may be found where the specific values of the thermal bridges are increasing when more insulation is added. In addition to the junction between floor slab and external wall (J1), the specific value of the thermal bridges increases in the junction between the external wall and the internal load bearing constructions (J2 & J3), roof construction (J4) and windows (J7).

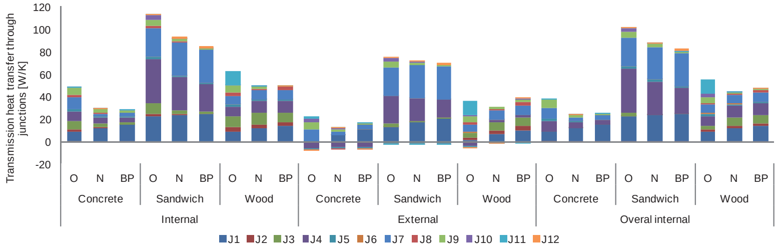

Fig. 7 The sum of transmission heat transfer losses in the investigated junctions, J1-J12, by different measuring method, exterior wall constructions and building categories. Building category abbreviations; O: Old building stock, N: New construction and BP: Best practice

4. Discussion

4.1 The survey

The survey showed that there is no widespread and established view among engineers and architects regarding how to quantify building elements as input for calculation of transmission heat transfer losses. Today, several consultants usually are involved in the design and construction phase of a building. It is possible to imagine a scenario in which the architect will be asked to provide quantities of building components and junctions, the construction engineer calculates U-values and specific values for thermal bridges based on these and the building services consultant or energy coordinator carries out the actual energy calculation. In this scenario, misunderstandings and therefore inaccurate calculations of transmission heat transfer losses may occur. An increased use of Building Information Modelling, BIM, in the design and construction of buildings may also be seen as a potential source of calculation errors if geometry and quantity take offs (data export from the model e.g. floor-, roof-, wall areas etc to text data) are used from the BIM model without a critical review of the data and geometry provided from the model. On the other hand, a standardized and automatic way to use correct data as input could minimize such errors.

Roughly a fifth of the respondents used the method of leaving out the calculation of thermal bridges and instead increased the transmission heat transfer through building elements by a certain percentage. However, the used percentage factor is generally lower than the factor which should be used according to the Swedish National Board of Housing, Building and Planning, in connection to this method.

The survey indicated that engineers and architects do not know or think about that a thermal bridge also, by definition, occurs when there is a difference between internal and external area. This was shown when the respondents were asked to assess whether different junctions increased the transmission heat transfer losses in addition to the losses included in building elements. This is alarming. If one does not think that a junction is a potential thermal bridge, one is not likely to carry out any analysis or calculation to investigate the effect on thermal transmission by the specific junction.

The survey was conducted among Swedish engineers and architects and the results should therefore be interpreted on the basis of that. If a more standardized method would have been defined, mandatory to use and described in guidelines, the results would hopefully have been different.

4.2 Influence of thermal bridges

In the relevant standards for energy calculations, used as a basis for this study, there is no defined “correct” measuring method. As shown, the specific values of the thermal bridges may vary depending on chosen measurement method. It is therefore important to strictly follow one measuring method in combination with relevant calculation method.

Many of the previous studies, mentioned in the introduction, highlights the need for dynamic calculations in order to correctly assess the impact of thermal bridges. However, this study investigates the effect of thermal bridges based on steady state calculations. Nevertheless, this study clearly shows the increased need of considering thermal bridges when calculating the transmission heat transfer through building elements and thermal bridges.

Heat losses from a building also occur due to ventilation heat transfer. In addition to the air flow rate due to mechanical ventilation, an additional air flow must be considered, due to infiltration. The infiltration is depending on the air permeability of the building envelope, which may be determined as defined in EN 13829 [49]. This standard clearly states that the reference area used to define air permeability, q_{50}, is based on overall internal dimensions. Based on these conditions, overall internal measurement may possibly be more suitable for calculating transmission heat transfer. Especially if an energy calculation software is used that calculates both the transmission heat transfer coefficient and the infiltration air flow based on the same area.

In all cases where the specific value of the thermal bridge increases when more insulation is used, it is due to a geometrical effect; the transmitting area increases. E.g. when more insulation is added to the exterior wall, the increased amount of insulation increases the window bays, thus increasing the transmitting area. The same effect is seen when more insulation is mounted towards interior load bearing constructions in concrete (floor slabs and walls). Since concrete has a high thermal conductivity, this means that the concrete slab, in general, has the same temperature as the indoor air. The increased amount of insulation therefore results in an increased interface area between the wall and the interior concrete construction. Consequently this also means an increase of transmitting area and a higher specific value of the thermal bridge. Also, the specific value of the thermal bridge towards the concrete floor slab increases due to the same effect.

The effect of increased specific values of thermal bridges occurs in this case study due to the assumption that the decreased transmission heat transfer is achieved by increasing the insulation thickness inwards, which is a common approach in Nordic countries. However, there are other technical solutions, available today, for exterior wall constructions where the increased thickness of insulation is increased outwards. By using the alternative technical solution this effect would not occur.

In design of new passive houses, low energy buildings or Net Zero Energy Buildings it is possible that junctions are given extra attention in order to decrease the effect of thermal bridges. Consequently, this would decrease the effect of the thermal bridges. However, today examples of newly built passive houses may be found both with innovative junctions and standard junctions [6].

The largest transmission heat transfer due to thermal bridges may be found in junctions between external wall and floor slab constructions, windows and attic floors. These junctions should therefore be in focus of future development of building systems and in the architectural and construction design of new buildings.

In general, building projects are unique projects where the specific conditions imply unique building elements and more or less unique solutions for the junctions between the elements. This study has tried to be consistent regarding junctions. This means that more or less the same technical solution has been used to connect the building elements, regardless of the amount of insulation.

5. Conclusions

5.1 The survey

The result from the survey shows that the state of knowledge is not satisfying among Swedish engineers and architects regarding different measuring methods and the effect on thermal bridges. Furthermore, no clear practice/norm can be identified regarding which measuring method that usually is applied. A need for clearer building regulations, development of guidelines regarding how to use available international standards and need of education/training of engineers and architects has been identified.

A well defined measuring system with the subscripts presented in Table 1 or clarification in text should always be applied in order to minimize the risk of misunderstandings when information regarding building element areas and thermal bridges are exchanged between engineers and architects or communicated in publications.

5.2 Influence of thermal bridges

The study clearly shows the increasing role of thermal bridges in transmission heat transfer calculations when improving the building's energy performance. This is true even though the specific value of thermal bridges may decrease when more insulation is added. The relative (percentage) effect of thermal bridges increases when more insulation is used. If values for normalized thermal bridges are to be used, they need to be differentiated by building system and different amounts of insulation.

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