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Renovation of Historic Wooden Apartment Buildings

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Declaration: *Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology, has not been submitted for doctoral or equivalent academic degree.*

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Ajalooliste puitkorterelamute renoveerimine

ENDRIK ARUMÄGI

TTÜ KIRJASTUS

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ABSTRACT

Historic buildings are an important part of the cultural heritage. In the course of time, the use of historic buildings has changed. Modern people have different requirements for comfort, function, and energy-efficiency of the buildings. The buildings in the milieu valuable areas are subject to demands set by different regulations, such as energy efficiency on the one hand and the heritage regulations on the other hand. Buildings in the milieu valuable areas are often seen as the conflict area of two different parties because of the different standpoints. The research uses the methods of large-scale field studies as well as computer simulations to analyse the performance of historic wooden apartment buildings.

In historic wooden apartment buildings the measured primary energy (PE) consumption was 331 kWh/(m^2·a), which is 84% higher than the minimum energy performance requirement for the buildings subject to major renovation in the energy performance regulation (180 kWh/(m^2·a)). A maximum of 63% reduction was achieved by use of a pellet boiler as a heat source combined with a heat recovery ventilation system, and with all the maximal insulation measures considered. The limit set in the regulation was reached. The results showed that higher energy savings from different insulation measures combined, without considering the building service systems, do not enable increased cost-effectiveness. Combining insulation measures with building service systems broadens the possibilities and higher energy savings can be achieved in an economically viable way. The results of the economic assessment and consideration of the milieu values indicate that the cost optimal 250 kWh/(m^2·a) could be reached and at current costs EPV≤180 kWh/(m^2·a) is achievable.

Indoor temperature was outside class III target values in 83% of the apartments in winter and in 25% of the apartments in summer. Indoor temperature variations reflect also the complaints concerning unstable temperature and cold floors during the winter period. The indoor climate conditions differ from those in more recent apartment buildings and it is necessary to improve the indoor thermal comfort.

For the hygrothermal analyses of the building envelope, the modelling curves of the indoor temperature and the moisture excess were derived from the measurement results. The probabilistic approach was applied to analyse the reliability of the interior thermal insulation as a retrofit measure. The results of the study show that a solution that involves design values with possible distributions considered is not reliable for the interior insulation.

A method to assess the influence of energy retrofit measures on the building level in the milieu valuable district was introduced and tested. Different renovation packages were analysed to find possible changes in the building appearance. Independent of the starting conditions, the whole building renovation is preferred over single insulation measures that are visually easier to detect. The results show that the energy performance of the historic wooden apartment buildings can be improved significantly without large negative influence on the architectural appearance and destroying the milieu value of the district.

Keywords: historic building, renovation of wooden apartment building, energy efficiency, indoor climate, interior thermal insulation, moisture safety, milieu value.

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KOKKUVÕTE

Ajaloolised hooned moodustavad olulise osa kultuuripärandist. Aja jooksul on ajalooliste hoonete kasutus muutunud. Tänapäeval on inimestel kõrgemad nõudmised hoonete mugavusele, toimivusele ja energiatõhususele. Miljööaladele jäävate hoonete osas kehtivad erinevad määrused, energiatõhususe määrused ühelt poolt ja muinsuskaitselised seadused teiselt poolt. Miljööaladele jäävad hooned on konfliktikoht, kui arvestada eelpool mainitud määrustes ja seadustes esitatud seisukohtade ja nõudmistega. Et uurida miljööaladel paiknevate korterelamute toimivust nii energiatõhususe, sisekliima ning niiskustehnilise toimivuse osas, on antud töös kasutatud laiaulatuslikke välimõõtmisi ja arvutisimulatsioone.

Mõõdetud energiatarbimise põhjal oli ajaloolistes puitkorterelamutes arvutatud keskmine energiatõhususarv ETA=331 kWh/(m^2·a), mis on 84% kõrgem kui energiatõhusus miinimumnõuete määruses esitatud piirsuurus oluliselt rekonstrueeritavatele hoonetele (ETA≤180 kWh/(m^2·a)). Maksimaalne arvutuslik renoveerimisega saavutatav primaarenergia (PE) kokkuhoid on 63%, mis on võimalik järgmiste renoveerimismeetmete rakendamisega: olemasolev küttesüsteem asendatakse pelletikatlal põhineva küttesüsteemiga, paigaldatakse soojustagastusega mehaaniline ventilatsioon ja tarindite osas vähendatakse maksimaalselt soojuskadusid. Majanduslike arvutuste tulemused näitavad, et hoonepiirete soojustamine panustamata tehnosüsteemide uuendamisse ei ole kulutõhus. Kombineerides hoonepiirete soojustamist tehnosüsteemide uuendamisega, laieneb kulutõhusate renoveerimispakettide hulk. Majanduslikud arvutused näitavad, et arvestades arhitektuurse välisilme säilimisega, võib pidada miljööaladel paiknevate puitkorterelamute renoveerimise kulutõhususarvu piirsuuruseks ETA 250 kWh/(m^2·a) ning praeguste kulutuse säilimisel ETA 180 kWh/(m^2·a) saavutamist.

Sisekliima mõõtmised näitasid, et korterite sisetemperatuur oli väljaspool sisekliima III klassi piirsuurusi talvel 83% ajast ja suvel 25% ajast. Sisetemperatuuri kõikumised peegeldavad hästi elanike kaebusi muutuva sisetemperatuuri ja külmade põrandate osas talvisel ajal. Ajalooliste puitkorterelamute sisekliimatingimused erinevad oluliselt kaasaegsete korterelamute sisekliimast, mis näitab renoveerimise vajadust.

Mõõtmistulemuste põhjal koostati mudel sisetemperatuuri ja niiskuslisa modelleerimiseks, mida saab kasutada hoone piirete niiskustehnilise toimivuse analüüsil. Kasutades stohastilist analüüsi, hinnati seespoolse lisasoojustuse toimivust, arvestades projektsuurustega ja nende suuruste tõenäosuslike hajuvustega. Analüüsi tulemusena leiti, et seespoolne lisasoojustus ei ole töökindel lahendus.

Miljööväärtuslike hoonete välisilme säilitamiseks on töös välja pakutud meetod energiatõhususe parandamise meetmete mõju hindamiseks. Meetodit kasutades hinnati erinevate renoveerimispakettide mõju miljööväärtusliku hoone välisilmele. Sõltumata hoone algolukorrast, on võrreldes üksikmeetmete kasutamisega eelistatud hoone tervikrenoveerimine. Tulemus näitab, et ajalooliste puitkorterelamute energiatõhusust on võimalik oluliselt parandada ilma, et see avaldaks olulist negatiivset mõju arhitektuursele välisilmele ja seeläbi ka miljööväärtuslikule alale.

Märksõnad: ajalooline hoone, puitkorterelamu renoveerimine, energiatõhusus, sisekliima, seespoolne soojustus, niiskusturvalisus, miljööväärtus.

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Tallinn, May 29th, 2015

Endrik Arumägi

CONTENTS

LIST OF PUBLICATIONS

This thesis is compiled mainly on the basis of the data presented in the following peer-reviewed journal articles:

I Arumägi, E., Kalamees, T. (2014). Analysis of energy economic renovation for historic wooden apartment buildings in cold climates. Journal of Applied Energy 115 (2014) 540-548.

II Arumägi, E., Kalamees, T., Kallavus, U. (2015). Indoor climate conditions and hygrothermal loads in historic wooden apartment buildings in cold climates. Proceedings of the Estonian Academy of Sciences 2015, 64, 2 146-156.

III Arumägi, E., Kalamees, T., Pihlak, M. (2015). Reliability of interior thermal insulation as a retrofit measure in historic wooden apartment buildings in cold climates. Energy Procedia 00 (2015) 000–000.

IV Arumägi, E., Kalamees, T., Mändel, M. (2015). Method for assessment of energy retrofit measures in milieu valuable buildings. Energy Procedia 00 (2015) 000–000.

and on the following peer-reviewed conference publications:

V Arumägi, E., Ilomets, S., Kalamees, T., Tuisk, T. (2011). Field Study of Hygrothermal Performance of Log Wall with Internal Thermal Insulation. In Proc. of the International Conference on Durability of Building Materials and Components, XII DBMC. Porto 2011.

VI Arumägi, E., Kalamees, T. (2012). Validation of a Simulation Model for Hygrothermal Performance of Log Wall with Internal Thermal Insulation in Cold Climate. In Proc. of the 5th International Building Physics Conference. Kyoto 2012.

These publications are referred to in the text by their Roman numbers.

AUTHOR´S CONTRIBUTION TO THE PUBLICATIONS

The author of the thesis is the principal author of all the publications.

In I, analysis of the measured data and the simulations were carried out by the author. The research principles of the study were developed by the co-author.

In II, the analysis of the measured data was made in cooperation with supervisor T. Kalamees. The air samples were analysed at the Centre for Materials Research of Tallinn University of Technology by the co-author U. Kallavus. The hygrothermal load model was derived, the results were discussed and conclusions were made by the author.

In III, the simulations and calculations were done by the author, the regression analysis was done in cooperation with the co-author M. Pihlak. The research principles of the study were developed in cooperation with my supervisor T. Kalamees. The results were discussed and conclusions were made by the author.

Article IV was written in cooperation with the co-authors.

In V, the measurements were prepared and performed in cooperation with my supervisor T. Kalamees. T. Tuisk from the Chair of Building Materials was involved in the determination of material properties. S. Ilomets was involved in field measurements. The results were analysed, discussed and conclusions were made by the author.

In VI, the research principles of the study were developed by the co-authors. The simulations and analyses of the results, discussion and conclusions were made by the author.

NOMENCLATURE

ach	Air change per hour, h^{-1}
AF200	Attic floor with additional thermal insulation +200 mm
AF400	Attic floor with additional thermal insulation +400 mm
AHU	Air handling unit
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
avg	Average
AWHP	Air-water heat pump
BAU	Renovation packages according to current renovation practice (business as usual)
BC	Base case
BF100	Basement ceiling with additional thermal insulation +100mm
DH	District heating
ECO	Renovation packages with the best economic effect
EL	Electricity
EPBD	European Union Energy Performance of Buildings Directive
EPC	Energy performance class
EPV	Energy performance value, $kWh/(m^2 \cdot a)$
EW20	External wall with additional thermal insulation +20 mm
EW70	External wall with additional thermal insulation +70 mm
EW120	External wall with additional thermal insulation +120 mm
EW170	External wall with additional thermal insulation +170 mm
EWS	Estonian Weather Service
GB	Gas boiler
HAM	Heat, air, and moisture
HER	Renovation packages that alter the architectural appearance the least to save heritage buildings
HR80	Ventilation system with heat recovery 80%
HVAC	Heating, ventilation and air conditioning
HDD	Number of heating degree-days per year at defined indoor temperature
ICCROM	International Centre for the Study of the Preservation and Restoration of Cultural Property
ICOM	International Council of Museums
ICOMOS	International Council on Monuments and Sites
IDA ICE	Multi-zone indoor climate and energy simulation program
IEQ	Indoor environmental quality
max	Maximum
min	Minimum
OB	Oil condensate boiler
RH	Relative humidity, %
st.dev.	Standard deviation
TRY	Test Reference Year

UNESCO	United Nations Educational, Scientific and Cultural Organization
W0.8	Window with U=0.8 W/(m^2·K)
W1.1	Window with U=1.1 W/(m^2·K)
W1.4	Window with U=1.4 W/(m^2·K)
W1.8	Window with U=1.8 W/(m^2·K)
WBS	Wood burning stove
WPB	Wood-pellet boiler
WUFI	Hygrothermal simulation program for the heat and moisture transfer in building envelope constructions
WWII	Second World War

A_{floor}	Heated net floor area of the building, m^2
c	Specific heat, J/(kg·K)
C_{G}	Global cost of the building in the renovated case, €
$C_{\mathrm{a,i}}$	Annual energy cost i €
C_e	CO_2 concentration of the outdoor air, ppm
$C_{G(\tau)}$	Global cost, NPV, €
C_G^{ref}	Global cost of the building in the reference case, €
C_i	initial investment cost €
$C_{i,0}$	CO_2 concentration at start of time period, ppm
$C_{i,t}$	CO_2 concentration at time “t”, ppm
$C_{l,i}$	Annual loan interest rate cost i €
cfu	Colony forming units (for air samples), cfu/m^3
D_{ws}	Liquid transport coefficient for suction, m^2/s
D_{ww}	Liquid transport coefficient for redistribution, m^2/s;
D_φ	Liquid conduction coefficient, kg/(m·s)
E	CO_2 generation rate, l/(h·pers)
G	Moisture production indoors, g/h
H	Total enthalpy, J/m^3
h_v	Latent heat of phase change, J/kg
M index	Mould index, -
n_{50}	Air leakage of building envelope at 50 Pa air pressure difference, m^3/(h·m^3) = h^{-1}
p	Statistical significance according to Student-s T-test
p	Water vapour pressure, Pa
pers.	Person
q_{50}	Air leakage rate of building envelope at 50 Pa air pressure difference, m^3/(h·m^2)
q_{v}	Ventilation air flow, m^3/h, l/s
R_a	Ventilation & infiltration airflow, m^3/s, l/s
$R_{d(i)}$	Discount factor for the year i, €
S_d	Equivalent vapour diffusion thickness, m

Z_p	Water vapour resistance with respect to partial water vapour pressure, $(m^2 \cdot s \cdot Pa)/kg$
τ	Time, s
T	Temperature, K
t	Temperature, °C
U	Thermal transmittance, $W/(m^2 \cdot K)$
V	Volume, m^3
w	Moisture content mass by volume, kg/m^3
σ	Standard deviation
δ_p	Vapour permeability, $kg/(m \cdot s \cdot Pa)$
η	Efficiency of the heat recovery
λ	Thermal conductivity, $W/(m \cdot K)$
μ	Water vapour diffusion resistance factor, -
ν	Humidity by volume, g/m^3
$\Delta\nu$	Moisture excess (the difference between the indoor and the outdoor air water vapour content), g/m^3
ξ	Porosity, m^3/m^3
ρ	Bulk density, kg/m^3
φ	Relative humidity, -
$_e$	External, outdoor
$_i$	Internal, indoor
$_{sat}$	Saturation

1 INTRODUCTION

1.1 Background

Estonian architectural history in the 20th century differs from the previous centuries. The reason is that for the first time architecture began to be commissioned by Estonian society and was designed for this society by Estonian architects (Kalm 2002). In many towns in Estonia well-preserved areas were built mainly before the Second World War. Currently these areas are listed as milieu valuable areas, meaning the coherent historical housing environment as assessed by planning experts (Semm 2012). Not all the buildings are formally protected, even so these buildings constitute an important part of the built heritage.

In the course of time, the requirements of the apartment buildings have changed. Modern people have different requirements for safety, health, comfort, function, and energy-efficiency of the buildings. For example, according to the census in 2000, there was hot water available in only 30% of the apartments in buildings in one of the milieu valuable areas in Tallinn (Talk 2014). Similar examples can be cited also for other properties of the buildings. The changed living standards and requirements of the buildings have caused a need for renovation on a larger or smaller extent.

In the mid-1980s several detail plans were made to replace the historical suburbs of Tallinn with contemporary housing (Alatalu 2012). Twenty years ago these areas were still seen as areas abandoned, like to squatters and criminals. During the last decade, the use of the real estate has strongly changed in the milieu valuable areas. The changing process of poor neighbourhoods into a popular and prosperous district has taken place. Today, the concept of a milieu valuable area is used by real estate agents for selling and renting apartments in deprived neighbourhoods that are institutionally acknowledged as the neighbourhoods with a milieu value (Semm 2012).

The buildings in the milieu valuable areas are subject to demands set by different regulations, such as energy efficiency on the one hand and the heritage regulations on the other hand. There is lack of information about the current conditions and renovation possibilities of the wooden apartment buildings in contrast to the prefabricated concrete or brick apartment buildings. The owners and heritage authorities do not always pursue the same goals when it comes to improving energy efficiency of the historical buildings. The buildings in the milieu valuable areas are often seen as the conflict area of these two parties because of the different standpoints.

In view of the fast increasing energy prices, living in buildings with low energy efficiency can become very expensive. It is common practice to upgrade the building envelope in order to enhance the energy performance of buildings. It is important to understand that historic buildings need a protection from unsuitable retrofit measures and the character of urban area must be preserved.

The cultural heritage values are rarely taken into account in the analysis and realisation of the potential of energy savings. In most cases, additional external insulation is the critical aspect and that is typically prohibited by municipalities in the milieu valuable areas. As a result, a strong pressure is encountered to use interior thermal insulation as a retrofit measure to improve the building envelope. Interior insulation could be a possible solution when the facade has a high value and must be preserved. Interior thermal insulation may cause hygrothermal risks. Thus, special requirements for the retrofit solutions and building service systems are set.

To preserve historical buildings, it is essential to have a good insight in the interaction of indoor climate, hygrothermal performance and energy performance, durability of building fabric, and milieu values of the buildings. To analyse the energy retrofitting and preserving the heritage values of the historical buildings, appropriate methodologies are required. However, relevant methodologies are rare. All the considerations above are strongly linked, relevant and real in today's situation. To achieve reliable performance with new materials and technologies introduced, it is important to evaluate retrofit solutions. Reliable assessment methods will lead to better prediction of the performance of renovation solutions and enable preventive measures to be taken into account, resulting in longer service life, better indoor climate, reduced use of energy, and preserved heritage values.

1.2 Objective and content of the study

The aim of the study is to analyse the renovation solutions for sustainable renovation of historic wooden apartment buildings to improve the energy efficiency, provide better hygrothermal performance and indoor climate. Indoor climate and hygrothermal performance of the building envelope are mandatory requirements to be fulfilled, a balance between energy savings and the preservation of the heritage values has to be found.

To achieve this aim in the interaction of indoor climate conditions, hygrothermal performance of the building envelope, energy savings, and preservation of the milieu values, the following objectives are addressed:

- an analysis of the energy performance in the present situation and evaluation of the energy saving potential in the historic wooden apartment buildings;
- an analysis of the indoor climate in the existing situation to determine indoor climate conditions and the hygrothermal loads for the performance analyses of the historic wooden apartment buildings;
- an analysis of the hygrothermal performance and moisture safety of the interior thermal insulation and to determine the reliability of interior thermal insulation on log walls;
- an analysis of the impact of the energy renovation measures on the milieu values of the wooden apartment buildings and to work out a method to assess the influence of the energy performance improvements of the historic

wooden apartment buildings on the architectural appearance and the milieu value of the district.

The thesis consists of four peer-reviewed journal articles and two conference papers (*see page 10*):

The technical potential and economic impact of energy renovation measures for historic wooden apartment buildings in Estonia are shown in article I. The relationship between the energy savings and different renovation strategies to improve the energy efficiency of existing buildings were analysed by combining single retrofit measures into renovation packages to attain energy savings from -20% as a minimum primary energy saving to -55% as PE requirement for existing buildings that are subject to major renovation; and “max” as the lowest PE consumption of simulation cases.

The current conditions and need for improvement of indoor climate in wooden apartment buildings is shown in article II. Based on the measurement results, indoor hygrothermal load model applicable to stochastic hygrothermal analysis was developed.

The performance and moisture safety of interior thermal insulation on a log wall is shown in articles III, V, and VI. Results from the field measurements of the hygrothermal performance of six interior thermal insulation solutions are covered in paper V. The measurement results are exploited in paper VI for the validation of the hygrothermal models for future simulations. The validated simulation model was used in article III for the probability analysis of the failure occurrence taking into account variability of different influencing factors.

Paper IV presents a method to assess the influence of energy renovation measures to the milieu value of the wooden apartment building. The method concentrates on finding energy renovation solutions for wooden apartment buildings by minimal influence on the milieu values.

The knowledge acquired in the research will be of scientific interest for the research community as well as renovation and conservation practitioners dealing with the indoor climate, building physics and energy performance of historic buildings. The newly acquired knowledge discussed in this thesis is as follows:

- the energy performance and saving potential of the historic wooden apartment buildings were determined;
- the indoor climate conditions and hygrothermal loads as well as needs for improvement were determined;
- the moisture safety of a log wall with interior thermal insulation was determined by the stochastic analysis;
- a method for selection of the energy renovation measures to minimise the milieu values of the wooden apartment buildings was developed and tested.

2 RENOVATION OF HISTORIC WOODEN APARTMENT BUILDINGS

2.1 Past and present

During the 20th century, and especially since the Second World War (WWII), protection of cultural heritage has grown to international dimensions, involving organisations such as UNESCO, ICCROM, ICOM and ICOMOS, the definition of charters, recommendations, guidelines, and conventions, as well as promoting awareness campaigns and developing specialised training activities. The concept of cultural heritage has been broadened from historic monuments and works of art to include ethnographic collections, historic gardens, towns, villages and landscapes (Jokilehto 1999). In this thesis, 'historic' refers to the time before WWII. The historic thresholds are well described in (Fabbri 2013).

Wood as a building material is widely used in many Nordic countries. In Estonia wood has been the main traditional building material over centuries. From the mid 1970s onwards, the attention of conservationists shifted also to wooden areas outside historical town centres – to suburbs erected in the process of rapid urbanisation at the end of the 19th and the first decades of the 20th centuries (Toss 1999).

Construction of wooden apartment buildings decreased significantly after WWII and finished practically after the 1960s (Figure 2.1). Most of the remaining wooden apartment buildings that originate from the end of the 19th century and the beginning of the 20th century are forming well-preserved entities (Figure 2.2). Not all the wooden apartment buildings built before WWII are formally protected; at the same time, these buildings constitute an important part of the built heritage. To protect the buildings, the areas with wooden apartment buildings are nominated as *milieu valuable areas*.

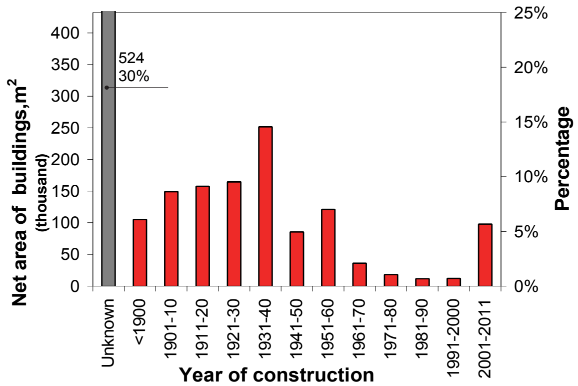


Figure 2.1 Distribution of wooden apartment buildings by year of construction in Estonia.

Figure 2.2 Illustrative photos of the historic wooden apartment buildings on the milieu valuable areas in Tallinn.

During the 1970s and 1980s (Soviet period), the suburbs were threatened to be demolished in vast areas, whereas after the privatisation the development of single plots started. In spite of the promotion of the historical suburbs, no protective steps were taken and the suburbs lost a remarkable part of their authenticity during the 1990s. The first protection areas were formed in Tartu in 1995 and 1996. Tallinn enacted eight milieu protection areas in 2001. The idea to protect historical areas and develop regulations on the municipal level was enacted with the new Planning Act from 2002 (Alatalu 2012). Today there are altogether 78 milieu valuable areas in Estonia.

According to the Planning Act (RT I 2002, 99, 579), a milieu valuable area is equal to a built-up area of cultural and environmental value that is essentially, clearly and specifically different cultural environment, which includes the residential areas created and designed by humans. Such areas encompass cultural and historical as well as social values and their preservation is important from both the cultural point of view and that of national and local identity. As for residential management, right and proper preservation and sustainable development of residential areas of cultural and environmental value is necessary for ensuring the quality and variety as well as long-lasting and reasonable use of housing stock (www.miljooala.ee).

In terms of legislation, a residential area of cultural and environmental value is an area determined by a plan where specific planning and building regulations are set connected with the area's historical and cultural peculiarities and the need to preserve them. Based on the Planning Act (RT I 2002, 99, 579) and the Building Act (RT I 2002, 47, 297), the areas of cultural and environmental value can be dealt with in the building regulations, the comprehensive plan, the thematic plan and the detailed plan on the local municipality level.

Comprehensive plans are prepared to determine the general directions and conditions for the development of the territory of a rural municipality or city, and of setting out the bases for the preparation of detailed plans for areas and in the cases where detailed planning is mandatory and to establish land use provisions and building provisions for areas where detailed planning is not mandatory. A comprehensive plan may be prepared as a thematic plan to specify or amend the comprehensive plan in force in accordance with different objectives. The objective of a comprehensive plan can be to designate built-up areas of cultural and environmental value, valuable arable land, parks, green areas, landscapes, individual features of landscapes and natural biotic communities, and to establish the provisions for their protection and use.

A detailed plan is prepared for a part of the territory of a rural municipality or city and it serves as the basis for short-term building activities and land use in the short term. The objectives of a detailed plan can be to designate, where necessary, built-up areas of cultural and environmental value and to establish the conditions for their protection and use. In the event of justified need, a local government council may initiate the preparation of a detailed plan for areas and in the cases where the preparation of a detailed plan is not mandatory to protect and set the terms of use and rules for constructions works on the area of cultural and environmental value.

For historic buildings, renovation solutions that concentrate on the building envelope are problematic due to the need for preserving the milieu values. In the course of time, the use of the historic buildings has changed. Today people have different requirements for thermal comfort, energy performance and functionality of the buildings. The problems of reconstructing historic apartment buildings were analysed by Sarv (2008). An underlying issue concerning additional thermal insulation of wooden buildings in milieu valuable areas with regard to the minimum energy efficiency requirements was analysed by Särgava (2010). The problem lies in unsuitable solutions during different times and the loss of original materials and details of the buildings. Several studies are targeted to helping building owners to overcome the problem concerning the lack of information about the original details of the historic wooden apartment buildings. Jüristo's studies (2007) concentrate on windows and window boarding. Muts (2010) analysed the specific profiles (horizontal weatherboards, vertical weatherboards, and dividing mouldings) characteristic of the period from the last quarter of the 19th century to the end of the 1930s, which allow restoration of a suitable original profile of the weatherboard. Küünarpuu (2014) made an inventory of 150 buildings about the extent of the initial building material preserved and gave an overview of the original details. The studies of Sepp (2004) and Nool (2007) cover two prevailing building types built at the beginning of the 20th century and propose adequate renovation techniques for the preservation of the buildings.

Developments in the protection of milieu valuable areas and the processes in these protected areas from 2001 to 2012 have been analysed and evaluated (Talk 2014). According to Talk, in general, the works that have taken place in the second half of the 2000s or later, when an accurate building regulation had been written, have preserved the architectural value of the buildings much more than earlier works. Thus, the building regulation has had a visible positive effect on the renovation practice.

Vast quantities of energy are consumed for heating and cooling to ensure standards of thermal comfort acceptable in today's terms (Chappells & Shove 2005). As the energy prices are rising fast, living in low energy efficiency historic buildings can raise the costs to keep the thermal comfort on an acceptable level. The cost of living has increased, and for many people, the standard of living is falling in line with a corresponding increase in fuel poverty (Nicol & Stevenson 2013).The first inevitable improvements have taken place in the renovation process of the historic wooden apartment buildings but improvements are still needed. Since we are living in a rapidly changing world, new knowledge is required to tackle challenges for sustainable renovation of historic buildings.

2.2 Energy performance

The average renovation rate in Europe is low, amounting to 1.2-1.4% per year. Thus it is estimated that by 2050, about half of the existing building stock in 2012 is expected still to be operational (Giancola & Heras 2014). Energy Roadmap 2050 (Brussels 2011) states that the prime focus should remain on energy efficiency, where buildings play a major role. Buildings represent the largest sector of primary energy consumption and play a major role in saving energy and reducing greenhouse gas emissions. Buildings are responsible for 40% of energy consumption in Europe (Bertoldi et al. 2012). In Estonia the share of buildings is much higher than the EU average, amounting to 50.2%, in 2011 and 2012 it was slightly lower, about 48% (EU-Directive 2010/31/EU). Apartment buildings in Estonia account for 51% of the total net area of dwellings (Kurnitski et al. 2014). The average heating energy used in historic wooden apartment buildings in Estonia is more than twice higher than that expected in today's new apartment buildings (I). Many studies (Balaras et al. 2007; Petersdorff et al. 2006; Lechtenböhmer & Schüring 2011) have indicated that the improvement of the building's shell of existing building stock hides large saving potentials.

Improvements of apartment buildings have raised their inhabitants' awareness of energy consumption in the building and have increased willingness to invest in energy saving solutions. Results (Balaras et al. 2005; Petersdorff et al. 2006; Lechtenböhmer & Schüring 2011) have indicated that the main savings potential lies in the improvement of the building's shell of existing building stock. Research by (Altan & Mohelnikova 2009) underlines the importance of such thermally insulated building envelopes together with new windows for the reduction of overall energy consumption. It was shown by (Morelli et al. 2012) that theoretical energy use can be reduced by 68% as compared to the energy use prior to the retrofit by the installation of insulation, new windows and a ventilation system with heat recovery.

Many studies discuss energy renovation of apartment buildings in a scale from building components through single buildings up to full building stock. Studies of energy-renovation have concentrated on historic buildings rather than on the energy saving potential of historic wooden apartment buildings.

Stovall et al. (2007) have examined wall retrofit options, including replacing the cladding, adding insulation under the cladding, and multiple sealing methods that can be used when installing replacement windows in well-built or loosely built rough openings. These results, combined with two analytical models, lead to annual utility cost saving estimates on the order of 10% for most locations. Additional savings are possible through the adoption of either low-e storm windows or replacement of vinyl-framed double-paned windows. Kaynakli (2012) presented a literature review about determining the optimum thickness of the thermal insulation material in a building envelope and its effect on energy consumption. In addition, in a practical application focus was especially on the determination of an economic insulation thickness. Häkkinen (2012) introduced a systematic approach for the development of refurbishment concepts for exterior walls, which is essential in order to enable comparisons of different refurbishment concepts, iteration and optimisation of alternative solutions, to set targets for the refurbishment of exterior walls, to avoid risks and to consider the whole building context. Konstantinou & Knaack (2011) assessed the impact of the retrofitted building components into the environmental performance of the building. Chantrelle et al. (2011) focused on the building's characteristics and performance using the multicriteria analyses concerning the interactions between the different objectives, and with identifying their convergences and divergences with an emphasis on building envelopes, heating and cooling loads and control strategies. Goldman et al. (1988) showed fairly good agreement on average, comparing pre-retrofit predictions with actual savings, although the variance for individual buildings was often quite large. In addition to the analysis of the building's energy saving potential and its influence on the architectural appearance, economic viability (Verbeeck & Hens 2005; Gustafsson 2000) is an essential issue because the cost of the measures varies according to the type of the measure, the type of the building, individual conditions and the circumstances of the renovation. Verbeeck & Hens (2005) discuss economically feasible ways and means to choose between insulation measures, better glazing, installation measures and renewable energy systems such as solar collectors and PV cells. Gustafsson (1998) adds that energy conservation measures might be profitable to be implemented even when a building is refurbished, depending, among other things, on the electricity and district-heating tariffs, the unit price for oil, etc. Bin & Parker's (2012) research combines material, energy and carbon emission studies covering the life cycle of the house, including the direct and indirect consumption of material and energy, and concomitant carbon emissions during its stages of material extraction, transportation, construction, operation, and demolition. Their study reveals that enhancing energy performance by renovation is an environmentally sound action for houses remaining in their service life for decades. This conclusion remains valid for more recent as well as century old houses which can easily achieve reductions in energy consumption by renovation. For historic, heritage, and traditional buildings, the improvement of energy performance should be a special case. The energy savings in historic buildings are a new research challenge (Fabbri et al. 2012; Fabbri 2013).

2.3 Indoor climate and hygrothermal loads

Building users consider thermal comfort to be the most important parameter influencing their overall satisfaction with IEQ, and thermal comfort is influenced by the type of the building, outdoor climate and season (Frontczak & Wargocki 2011). Oreszczyn et al. (2006) have quantified the variations in the indoor temperatures in the heating season, which are explained by the characteristics of a dwelling and a household and by energy efficiency improvements. Some very low indoor temperatures were indicated, which reflect a combination of the efficiency of the heating system and insulation, the capacity (maximum rate of energy consumption) of the heating system and personal choice/behaviours. In their review of domestic dwelling temperatures during the heating season, Hunt & Gidman (1982) conclude that the age and the type of the heating system have a strong influence on the temperature model.

The indoor temperature is considered the most important factor to assess the thermal comfort in the building. In addition, the indoor humidity is necessary in the assessment of the building performance. Indoor air humidity data in buildings are needed for many purposes. Indoor air humidity loads have been investigated in different field studies. Kalamees (2006) has presented a thorough literature review about the moisture excess in dwellings, showing a large variance in the results and pointing out short measurement periods. Geving & Holme (2012) studied the mean and diurnal indoor air humidity loads in residential buildings and concluded that measurements of the indoor air humidity should be made on a long-term basis.

Often moisture problems in cold climates relate to high indoor humidity levels in winter. In cold climates, excessive indoor humidity can lead to moisture accumulation with its many unwanted consequences, including microbial growth, poor indoor air quality and potential health problems for the occupants (Glass & Tenwolde 2009; Bornehag et al. 2004). The most frequently occurring spores are usually also the spores with the highest health risk. Depending on the indoor climate conditions and human response to the irritants, the number of spores in the indoor air need not be very high to cause health problems.

Asikainen et al. (2013) pointed out that large numbers of residences in European countries have mean ventilation rates below the requirements of the national building regulations or codes. The residents play an important role in the ventilation level in their own homes. Surveys of occupants showed that people generally think that ventilation is important, but their understanding of the ventilation systems in their houses is inadequate. The chain of activities from design through execution to use and maintenance, especially which of mechanical ventilation systems, shows weak links. Higher set points required to achieve adequate ventilation are infrequently used due to the noisy fans. Thus, poor use and lack of occupants' knowledge seem to be main problems in the under-ventilated homes (Dimitroulopoulou 2012).

Reasons for low temperatures and air change rates in the historic buildings often lie in the old building systems that have not been upgraded. A relation between the occurrence of mould growth and indoor air humidity levels was presented by (Oreszczyn et al. 2006). High levels of humidity and some surface and interstitial condensation may be sufficient for mould growth that may occur due to water damage from leaks, flooding and groundwater intrusion or due to construction faults, including inadequate insulation, in combination with poor ventilation (WHO 2009). Su (2002) found that visible mould growth on indoor surfaces is a relatively common problem in aged residential buildings that lack sufficient insulation. By improving the building envelope with additional insulation, it is possible to increase thermal comfort, save energy and lower the risk of mould growth and condensation on indoor surfaces. For reasons of preserving architectural appearance, facade changes of historic buildings are often prohibited. Internal insulation is a possible solution when a high value architectural appearance must be preserved. However, internal thermal insulation may cause hygrothermal risks; thus, special requirements are set for the renovation solutions. In addition to the material properties, the boundary conditions are also important (Zhao, Plagge, Nicolai, et al. 2011). To achieve moisture-safe buildings, data concerning deterministic and stochastic indoor humidity loads for the design and risk analysis must be accurate (Hens 2000; Mjornell et al. 2012).

Indoor temperatures vary by the building type and the construction. Field data about the indoor climate conditions in historic wooden apartment buildings are scarce. Unless measured conditions are available, realistic estimates of the boundary conditions are needed (Glass & Tenwolde 2009). Indoor temperature and humidity conditions are essential data for the assessment of indoor climate and thermal comfort as well as the hygrothermal performance of the historic buildings.

2.4 Interior thermal insulation

Due to the regulations, no changes outside the external wall on the facade are allowed to be done. Interior thermal insulation may cause hygrothermal risks and special requirements for solutions have to be set if interior insulation is found to be a possible solution. The low temperature of the log layer has an effect on the partial vapour pressure conditions and can cause moisture risks on the log layer between the log and the interior insulation (Ojanen 2007). It is possible to eliminate the problem of moisture diffusion with vapour retarder, but the problem with moisture convection may still stay (Ojanen & Simonson 1995). External thermal insulation is hygrothermally a much safer solution than internal thermal insulation.

Nevertheless, many studies (Stopp et al. 2001; Maděra 2003; Häupl et al. 2004; Toman et al. 2009 Juhart et al.2005) have analysed the possibilities to use the interior thermal insulation for improving external wall structures. Even if the risks and solutions of interior thermal insulation are presented, most of these studies are concentrated on stone walls, as a typical wall structure in Central Europe, but not so much on to the log walls. Ojanen (2007) has studied numerically the effect of internal thermal insulation on log walls and concluded that the vapour resistance of the inside sheathing layers sets requirements for the thickness of internal thermal insulation in cold climate conditions. Saarimaa et al. (1985) and Koski et al. (1997) have analysed hygrothermal performance of additionally insulated log walls in Finland by visual inspection and mostly by momentary measurement of moisture content. Comparison of different materials and envelope solutions is necessary because they affect hygrothermal performance in different ways. It is possible to study many buildings with momentary measurement, but it is not clear if the measurement period is sufficiently critical over the whole year. Therefore, long-term measurements are needed.

It is not economical and not even always possible to use in situ measurements for the assessment of the hygrothermal performance of the wall. The heat, air and moisture (HAM) calculation programs have good tools to investigate the hygrothermal performance of the wall. Today there are different simulation programs for the hygrothermal analysis of the building envelope to help architects and engineers during design processes. With the simulation programs it is possible to assess the heat, air, and moisture flow through the building envelope in different climatic conditions. The program can also help to select renovation solutions with respect to the hygrothermal response of building assemblies subjected to various climates.

Results of the simulations are influenced by different input data, such as wall construction details, material properties, initial conditions, and climate conditions. For more reliable results, the simulation models need to be validated based on laboratory or field tests.

Typically, to assess the hygrothermal performance and the moisture risks of the constructions, the deterministic approach is used in the design process. The reliability can be defined as the probability for a solution to function without failure during a given interval of time. The reliability concept fundamentally requires the assessment of probabilities, calling for the application of probabilistic methodologies rather than deterministic techniques (Janssen 2013). The different parameters influencing the hygrothermal performance of the retrofit measure have a stochastic nature. A stochastic method enables variations in material properties, climatic conditions, boundary conditions and differences in wall assemblies to be considered. The analyses can be carried out through testing the influence of a single input parameter on testing all the input parameters.

In several studies, stochastic approach has been applied in the analysis of hygrothermal performance. The influence of material properties is reported in (Salonvaara et al. 2001; Holm & Kuenzel 2002; Zhao, Plagge, Nicolai, et al. 2011), the influence of one part of the wall assembly in (Wang & Ge 2014), the performance assessment of interior insulation in (Zhao, Plagge & Grunewald 2011), and the performance of the building envelope in (Pallin 2013).

As a rule of thumb, the view established among designers is that a 50 mm interior insulation of mineral wool with a vapour barrier is a safe solution and can be easily applied as a retrofit measure in Estonia. For the case study, the measurements were performed inside the retrofitted walls in the typical historic wooden apartment building (V). After one and a half year, the occupants of the apartment started to complain about their children's' health problems. The walls were opened and heavy mould growth was detected. Also, the opening of the retrofitted walls revealed differences between the design and the execution. The question about the reliability of the interior insulation arose.

2.5 Consideration of the values of the milieu valuable buildings

To nominate the areas of cultural and environmental value, the architectural historic value of the buildings of the area is assessed. During the evaluation, the architectural, historic and urban developmental value of the building is taken into account. The buildings are graded and can have values using the following system:

- Cultural monument – building under state protection, which is of architectural, historical or urban developmental value and due to which it is designated as a monument pursuant to the procedure provided for in the Heritage Conservation Act.
- Highly valuable – building which is of architectural or urban developmental value and worth preserving as an outstanding example of the region, era, style, creation of architect or building type.
- Valuable building – remarkable example of architecture or significant in the history of the region. It can be both pronounced as a part of the milieu and different from the milieu.
- Milieu valuable building – is a typical building of the area, the value of which lies primarily in the function being a part of the group of typical buildings; also, buildings that are discounted from the higher value because of the changes in the appearance as a result of the reconstruction or with the loss of the original details.
- Low-value building – disregarding the milieu by volume and structure and thereby being a building with no architectural value. Low-value building in original state could have been a valuable building, but during reconstruction has lost the original and authentic appearance.

There is an exception concerning the buildings that are graded as cultural monuments. The buildings that are ranked and listed as cultural monuments should be preserved and restored in accordance with the Heritage Conservation Act (RT I 2002, 27, 153). For other buildings, the rules and restrictions are set in the Planning Act. In the case of highly valuable, valuable and milieu valuable buildings, the design criteria must be drawn, including the architectural requirements that specify the value of the building and the details of the building that are worth preserving. The design criteria must be prepared before any construction works by the company that holds the activity licence issued by the National Heritage Board and has to be done before any construction works. The main principles to follow are: all the decorative details of the facades, doors, porches, window sills and other details must be preserved; renewal must comply with the details made of the same material and with the same profile; the distribution of the facade and the eaves line must be preserved; attic floor can be used if the existing volume is not changed; the extension, reconstruction or substitution is decided on the basis of the preliminary design case by case taking into account the neighbouring buildings and environment.

The guidelines are more precise for the facade and finishing of the external walls. It is prohibited to use imitating materials: metal and plastic exterior finishes, plastic windows, metal doors, stone imitation and profiled roofing sheets; all architectural small constructions and parts must be in accordance with the environment and architectural appearance of the building; for the painting, the colours made of traditional materials and colours that are for painting wood must be used; facade repairs, the change of the external cladding and the change of the cladding material, change of windows and doors are not allowed without facade finishing permit; and if the buildings are insulated from the outside, the characteristic protrude of the basement wall and firewalls must be preserved, the windows must be moved outside so that they are at the same distance from the cladding surface as in the original state. Neither is it allowed to have any pipes diverting the combustion products from the heating devices to atmosphere on the facades.

Historic buildings are an important part of cultural heritage, the preservation of which is important for society and culture. It is our target to work out the principles and guidelines for the preservation of historic values for the future generations. Additional exterior thermal insulation of historic building is a challenge. It may cause a significant visual change as well as a loss in original material, thereby reducing the value of a historic building and conflicting with the preservation target. Consequently, in principle, in those buildings, such kind of insulation is rejected.

In addition to a single building, also a district can be valuable for its distinctive character. Important elements that express the character are defined mainly as an urban pattern, the formal appearance of buildings (both interior and exterior, defined by scale, size, style, construction, material, colour and decoration) but also the various functions the area has acquired over the time (Icomos 1987). In Estonia the valuable districts are protected as designated conservation areas or milieu valuable areas. Focus in this study is on historic buildings in milieu valuable areas, as the heritage restrictions are slightly milder (only the exterior of buildings is defined as valuable) and the buildings in milieu valuable areas are not merely protected.

In the near future, large numbers of the wooden apartment buildings in Estonian milieu valuable areas will require major renovation (Klõšeiko 2011). Historic buildings are subject to demands set by different regulations as thermal comfort, hygrothermal performance and energy efficiency regulations on the one hand and the heritage regulations on the other hand. Historic buildings are often seen as the conflict area of different parties because of the different standpoints. The owners and heritage authorities may not pursue the same goals when it comes to improving living conditions and energy efficiency and preservation of the historical buildings. Before any assessment of the influence of different energy renovation measures on the values of the building, it is important to determine the status of the existing building. This is emphasised and described as the first step in the 3B-method. The method is under development to work out a supporting tool to develop safe concepts for energy saving measures in different types of buildings (Arfvidsson 2014). Finding solutions to conflicts that arise when energy efficiency requirements are applied on architectural heritage is an acute research topic in many countries. A Norwegian study focused on timber-frame buildings in order to illustrate the potential for and problems with energy-efficiency measures. Their analysis was based on an evaluation of selected standard interventions applied towards different energy targets (Grytli 2012). Many international projects have been initiated and completed. The aim of the SECHURBA project was to demonstrate the opportunities and potential prospects associated with sustainable energy intervention in historic urban areas so that historic areas will be given greater priority in future energy policies and local development programmes (SECHURBA). The European project 'Efficient Energy for EU Cultural Heritage' bridges the gap between the conservation of historic buildings and climate change and demonstrates the feasibility of energy-efficiency measures in historic buildings (3ENCULT). Research project 'Energy Efficiency for EU Historic Districts' EFFESUS focuses on the energy efficiency of European historic urban districts and developing technologies and systems for its improvement (EFFESUS). The aim of the Co2olBricks project was to find solutions for raising energy efficiency in historic buildings without destroying their historic values; it was concluded that overall higher level of energy efficiency rehabilitation of historic buildings can be reached (Co2olBricks). The majority of the abovementioned methods take into account single measures or structures but seldom concentrate on junctions of structures that usually have the strongest influence on the visual character of the building.

3 METHODS

3.1 Studied buildings

In this study, first, the current state and renovation needs of historic wooden apartment buildings were determined. Altogether 29 buildings and 41 apartments built before WWII, with an average age of 98 years, were investigated in Tallinn, Tartu, Pärnu, and Viljandi (Table 3.1). The buildings were selected in cooperation with National Heritage Board, Culture and Heritage Departments of municipalities, Information Centre for Sustainable Renovation and Estonian Union of Co-operative Housing Associations. Also, personal communications were used.

Table 3.1 Construction time and location of studied historic wooden apartment buildings

Location	Number of studied buildings and apartments							
	<1900		1900-1920		>1920		Total	
	Buil-dings	Apart-ments	Buil-dings	Apart-ments	Buil-dings	Apart-ments	Buil-dings	Apart ments
Tallinn	-	-	5	6	6	10	11	16
Tartu	1	1	5	7	1	1	7	9
Pärnu	2	3	2	3	-	-	4	4
Viljandi	3	4	1	1	3	5	7	10
Total	6	6	13	13	10	10	29	41

The studied buildings occupy a volume of about 490 to 980 m^3, with the heated area between 242 to 823 m^2. Apartments of up to three rooms, with a separate kitchen, entry and sanitary rooms, in historic wooden buildings were studied. The average area of an apartment was 59 m^2.

Typical wall structures of the buildings consisted of horizontal or vertical logs with an external wooden cladding or render (Figure 3.1 – Figure 3.3). The typical wall thickness was between 150…200 mm. The buildings had two-pane windows with wooden frames. The attic floor is filled with a mix of sand and sawdust as insulation materials.

Historically, the requirements for the thermal transmittance of the external wall were set. In building regulations from the 1930s the limit for the thermal transmittance value $U \leq 1.0$ kcal/(m2·h·K) (1.17 W/(m^2·K) (RT 59 – 1932, art. 495) and $U \leq 0{,}9$ kcal/(m^2·h·°C) 1.05 W/(m^2·K) (RT 43 – 1937, art. 386) for the external wall of the dwelling can be found.

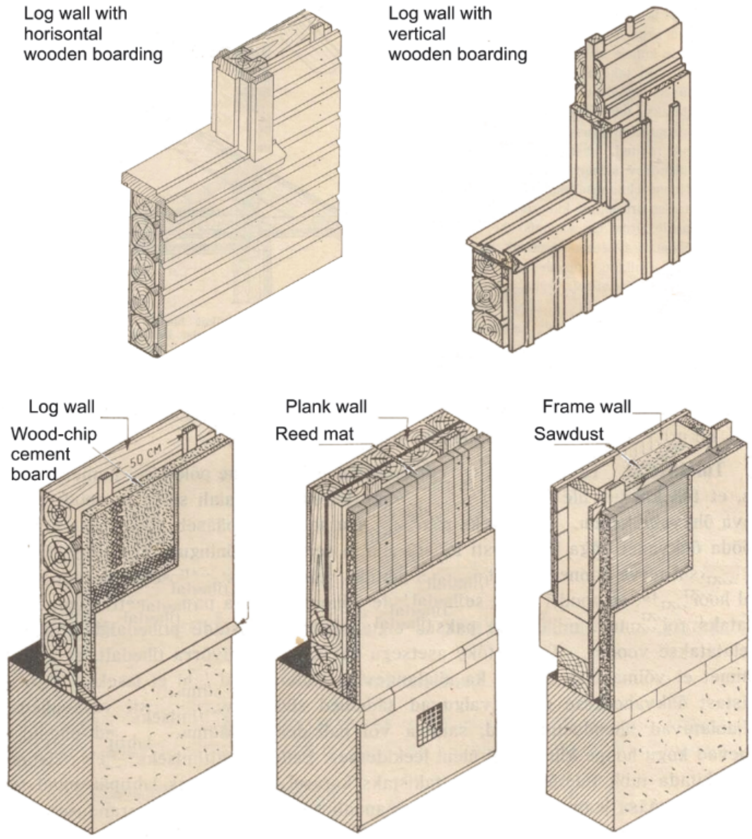


Figure 3.1 Typical external walls of wooden apartment buildings (based on Veski 1943).

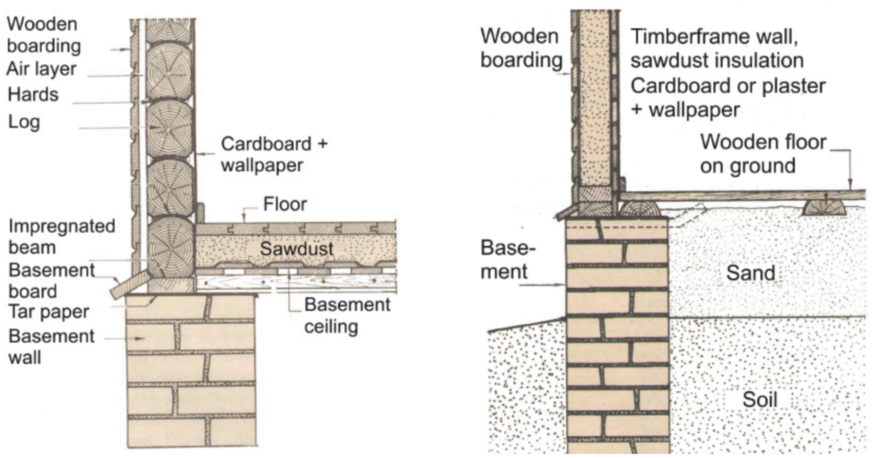


Figure 3.2 Connection of the external wall, basement and floor (building with a cellar (left); wooden slab on the ground (right) (according to Veski (1943)).

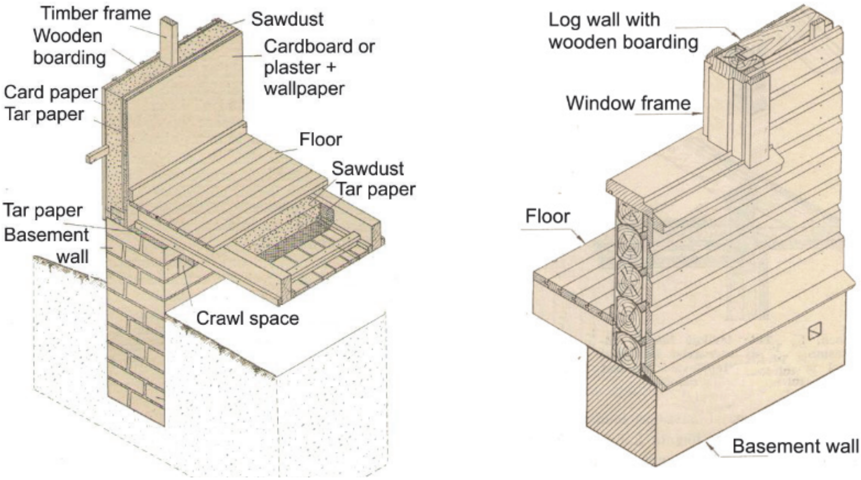


Figure 3.3 Connections of the exterior wall with floor (left) and window (right) (based on Veski 1943).

Original heating systems were wood burning stoves. In 65% of the studied buildings, the apartments were heated by a wood heating stove (original) and in 35% by radiators (new heating system). The heat source for the radiator system was mainly electricity or a gas boiler and in one of the buildings district heating. Most of the buildings were equipped with an electrical boiler to heat the domestic hot water. The studied buildings had natural passive stack ventilation. In general, the discharge takes place through the chimneys and the compensation through the building envelope, which means that the air change rate in the historic wooden buildings depends on the air tightness of the building. The reason is in the absence of fresh air valves in the majority of cases.

For indoor climate and energy simulations, four reference buildings were selected based on the size and representativeness of a typical historic wooden apartment building (Figure 3.4). Figure 3.5 shows the cumulative distribution of the closed net area and the living space area of the reference buildings and all wooden apartment buildings in Estonia.

Reference building A, referred to as ”Lender’s building“

Reference building B, referred to as “Tallinn’s building“

Reference building C, referred to as “Tallinn’s building”

Reference building D, referred to as “Workers building“

Figure 3.4 Reference buildings for indoor climate and energy simulations.

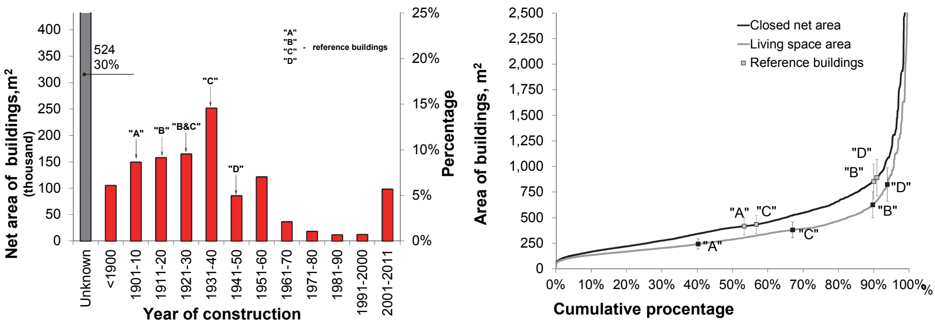


Figure 3.5 Distribution of the closed net area and the construction year (left); cumulative percentage of the net area and the living space area of the whole stock of wooden apartment buildings and the reference buildings (right).

All the buildings have simple floor plan (Figure 3.6), with a central staircase made of brick in buildings “B” and “C” (Tallinn’s building) and made of wood in buildings “A” and “D” (“Lender’s building” and after WWII building). Building “D” had no basement and the 1st floor is on the ground, buildings “A” to “C” are with a basement floor. Key characteristics describing the size and shape of the reference buildings are presented in Table 3.2.

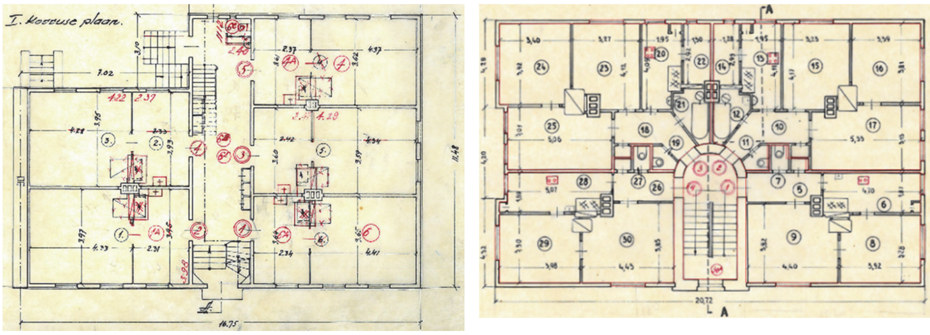


Figure 3.6 Floor plans of typical wooden apartment buildings (reference “A” and “B”).

Table 3.2 Key characteristics of the reference buildings in energy simulations

Characteristics	Reference building			
	“A”	“B”	“C”	“D”
Number of floors [a]	2+1	3+1	2+1	2
Number of apartments in original design	10	12	8	16
Area under building, m^2	170	269	183	506
Closed net area, m^2	416	852	433	891
Heated area, m^2	295	672	283	823
External wall area, m^2	370	667	469	467
Area of windows and doors, m^2	68	122	49	153
Ratio of external wall area and heated volume, m^{-1}	0.76	0.68	0.79	0.65
Thermal transmittance of building envelope U, $W/(m^2 \cdot K)$				
External wall	0.65	0.65	0.57	0.51
Basement wall	1.46	1.45	1.31	-
Windows	2.9	2.9	2.9	2.9
Attic floor	0.50	0.42	0.59	0.66
Basement floor	0.50	0.52	0.53	0.46
Air leakage rate of building envelope q_{50}, $m^3/(h \cdot m^2)$	5.6	7.5	11.1	10.3

[a] 2+1 means a total of 3 floors (2 floors with apartments and basement floor)

3.2 Energy performance and energy saving potential

3.2.1 Energy use and classification of the historic wooden apartment buildings

The energy use of the buildings was analysed based on the data of the electricity, gas, district heating, firewood, and water usage. Data for each building were collected from the suppliers on a monthly basis over a three to four year period. The consumption of the firewood for room heating was obtained from the apartment owners. In the absence of more accurate data, the energy used for heating in the buildings was estimated based on the information about the firewood consumption in the apartments.

The energy performance of buildings in Estonia is expressed as an annual primary energy (PE) usage and presented as the energy performance value (EPV, kWh/(m^2·a)). The total PE consumption includes the heat and fuel consumption for room heating, heating of ventilation and infiltration air, domestic hot water, and cooling as well, electricity for lighting, electrical appliances, and technical systems. The PE is calculated from the total delivered energy (DE) multiplied by the weighting factors for energy carriers (RT I, 05.09.2012, 4):

- wood and wood-based fuels (excl. peat and peat briquettes): 0.75;
- district heating: 0.9;
- fossil fuels (gas, oil, coal): 1.0;
- electricity: 2.0.

To be able to compare and classify the energy performance of buildings, the Energy Performance Classes (EPC) were used (RT I, 05.09.2012, 4). The smaller the EPV, the more energy efficient the building is. Apartment buildings are divided into the EPC according to the EPV:

- EPC H: EPV $\geq$ 341 kWh/(m^2·a);
- EPC G: 280 < EPV $\leq$ 340 kWh/(m^2·a);
- EPC F: 220 < EPV $\leq$ 280 kWh/(m^2·a);
- EPC E: 180 < EPV $\leq$ 220 kWh/(m^2·a);
- EPC D: 150 < EPV $\leq$ 180 kWh/(m^2·a) (criteria for major renovation);
- EPC C: 120 < EPV $\leq$ 150 kWh/(m^2·a) (criteria for a new building);
- EPC B: 100< EPV $\leq$ 120 kWh/(m^2·a) (criteria for a low-energy building);
- EPC A: EPV $\leq$ 100 kWh/(m^2·a) (criteria for a nearly zero energy building).

3.2.2 Indoor climate and energy simulations

The simulations were used to calculate the energy use for indoor climate, to predict the energy savings and to propose the retrofit measures. The multi-zone indoor climate and energy simulation program IDA Indoor Climate and Energy 4.5.1 (IDA ICE) (Sahlin 1996; Björsell et al. 1999) was used for the indoor climate and energy simulations. IDA ICE is a tool for building simulations of energy consumption, indoor air quality and thermal comfort validated in different studies (Moinard & Guyon 2000; Travesi et al. 2001; Iea et al. 2003; Woloszyn & Rode 2008). Simulation models were calibrated based on a building survey, field measurements of energy usage, user behaviour, measured indoor climate, and air tightness results.

The energy renovation measures were simulated with the standard use (RT I, 18.10.2012, 1) of the building to reduce the influence of the user behaviour. The indoor temperature set point during the heating season was $t_i \geq 21$ °C. For the reference case (not renovated), the airflow by natural passive stack ventilation was 0.35 l/(s·m²) per heated area, representing the indoor climate category III (EN15251). Even the real ventilation airflow could be smaller, this ventilation airflow was used not to make energy savings from bad indoor climate. In renovated cases, the ventilation airflow was 0.42 l/(s·m²) per heated area according to the indoor climate category class II (EN15251). For the specific use of domestic hot water (DHW), 520 l/(m²· a) was used. Internal heat gains were as follows: lighting (8 W/m²) with a usage rate 0.1; appliances and equipment (2.4 W/m²) with a usage rate 0.6 and with the utilisation factor 0.7; the heat from the inhabitants (2 W/m²) with the building usage rate 0.6. For outdoor climate, the Estonian TRY (HDD 4160 °C/d at t_i +17 °C) (Kalamees 2006) was used.

Infiltration rate was calculated by a simulation model using the average air leakage rate from the air tightness measurements, indoor and outdoor temperature, building geometry, air pressure constants and wind speed. The air tightness of each building was measured with the standardised fan pressurisation method (EN13829), using “Minneapolis Blower Door Model 4” equipment with an automated performance testing system (flow range at 50 Pa 25 m^3/h – 7800 m^3/h, accuracy ±3 %).The average air leakage rate at 50 Pa (q_{50}) pressure difference of all measured buildings was 10.5 $m^3/(h \cdot m^2)$ and the air change rate (n_{50}) was 12.5 h^{-1}. The reference case is a building with its original structure, stove heating and natural passive stack ventilation.

Efficiency factors for energy sources and heat distribution systems were taken into account in the energy calculations as presented in Table 3.3.

Table 3.3 Efficiency factors for energy sources and distribution systems

		Efficiency factor, -	
		Room heating	Domestic hot water
Energy production			
WBS	Wood burning stoves (original)	0.6	
WPB	Wood-pellet boiler	0.85	0.85
OB	Oil condensate boiler	0.9	0.9
EL	Electricity	1.0	1.0
DH	District heating	1.0	1.0
GB	Gas boiler heating	0.95	0.95
AWHP	Air-water heat pump	2.4	1.8
Heat distribution			
Wood burning stoves		0.85	
Hydronic radiators		0.97	
Electric radiators		1.0	

3.2.3 Energy renovation measures

In this study, renovation measures for the improvement of indoor climate and energy performance of historic wooden apartment buildings were selected, provided that urgent repairs to guarantee safety of buildings (mechanical resistance and stability, safety in use, safety in case of fire) will be done prior to energy renovation. Therefore, these works are not listed in this study. Neither do the renovation works here include protection against noise, improvement of architectural planning, visual quality, overall living quality, and additional comfort because these aspects were outside the scope of this thesis. In the renovation of historic wooden apartment buildings, these aspects should also be taking into account.

Energy renovation measures were applied to:

- the building envelope:
  - facade,
  - attic floor,
  - windows-doors,
  - base floor, basement ceiling,
  - foundation wall,
- and the building service systems:
  - room heating,
  - ventilation,
  - domestic hot water,
  - energy source.

The thickness of additional thermal insulation (λ=0.04 W/(m·K)) for the facade varied between 20…270 mm, for the attic floor 100… 400 mm, and for the basement floor 100…200 mm. Four renovation measures for windows were considered from the renovation of original windows (U=1.8 W/(m^2·K)) up to the installation of new windows (U=0.8 W/(m^2·K)) (see Table 3.4).

If the renovation measure enabled a reduction in air leakage, the air leakage rate of the building envelope was assumed to reduce from the original value down to 40%: 5% at the renovation of windows, 10% in the case of new windows, 5% at the insulation of attic floor, 5% at the insulation of base floor and 15% at the insulation of external walls.

For the energy source and heating system, the replacement of existing stove heating with a wood-pellet boiler (WPB), a district heating with substation (DH), a gas condensing boiler (GB), or an air to water heat pump (AWHP) as new heat sources with hydronic radiators were considered as renovation measures. The supply-exhaust air-handling unit (AHU) with heat recovery as a renovation measure was considered to improve the outdoor air flow rate in the building.

The energy renovation measures were combined in packages to gain different energy saving levels:

- decrease of 20 % of PE as a minimum primary energy saving,
- decrease of 55 % of PE as a PE requirement for existing buildings that are subject to major renovation,
- "max" with selected energy-renovation measures as the lowest PE consumption of simulation cases.

For each energy saving level, the packages were combined according to the current renovation practice (BAU), packages that alter the architectural appearance the least to save heritage buildings (HER), packages with the best economic effect (ECO). These three can be seen as representative of the different attitudes of different building owners. In BAU the insulations measures are considered first and building service systems are the second. In HER the least visible measures are considered first. In NPV the most economic measures are considered first. In each package, the min number of measures to reach the target level of energy savings was used.

Table 3.4 Description of the energy-renovation measures

Renovation measure	Detailed description
	Building envelope
AF200. Attic floor +200 mm insulation AF40. Attic floor +400 mm insulation	• additional thermal insulation installed to the attic floor +200mm or +400mm respectively; • reduction of air leakages by tightening and installation of air- and vapour barrier.
BF100. Base floor, basement ceiling +100mm insulation	• additional thermal insulation +100mm installed to the floor or basement ceiling or constructing a new floor with 100 mm insulation.
W1.8 Repair of window $U=1.8\ W/(m^2\cdot K)$ W1.4. New window $U=1.4\ W/(m^2\cdot K)$ W1.1. New window $U=1.1\ W/(m^2\cdot K)$ W0.8. New window $U=0.8\ W/(m^2\cdot K)$	• improvement or repair of the existing windows: repair of frames, new low emissivity (ε≈0.2) glasses, new gaskets; • replacement of existing windows with new windows (double or triple low emissivity (ε≈0.05) glazing) and moving them outwards so that the outlook of the buildings is similar to original.
EW20. External wall +20 mm insulation EW70. External wall +70 mm insulation EW120. External wall +120 mm insulation EW170. External wall +170 mm insulation EW220. External wall +200 mm insulation	• additional sheathing to the wall +20mm; restoration of original or installing of new wooden boarding with air layer between boarding and sheathing; • additional thermal insulation 50 mm, 100 mm, 150 mm, 200 mm between wooden scantling + sheathing to the wall +20mm; air barrier between insulation and original log wall; restoration of original or installing of new wooden boarding with air layer between boarding and sheathing; insulation on basement wall with similar thickness with external wall.
	Improvement of HVAC systems
HR80. ventilation system	• installation of balanced ventilation system with heat recovery (η≥0,8); providing airflows according to EN15251 II class;
DH. district heating GB. gas boiler heating WPB. pellet boiler AWHP. air to water heat pump	• change of heat source and heat supply system for room heating and DHW production; improvement of efficiency in heat production and heat distribution; installing a new heating distribution system with hydronic radiators.

3.2.4 Economic calculation of renovation measures

The economic effect of the renovation measures was assessed through a balance of investment cost and energy savings.

Global cost (the net present value (NPV), Eq. 1), considering the investment cost over a 20 year period) was used to assess the economic effect of the renovation measures (EN 15459):

$$C_{G(\tau)} = C_i + \sum_{i=1}^{20} (C_{a,i} + C_{l,i}) \cdot R_d(i)) \qquad \text{Eq. 1}$$

where $C_{G(\tau)}$ is the global cost, NPV, €; C_i is the initial investment cost €; $C_{a,i}$ is the annual energy cost *i* €; $C_{l,i}$ is the annual loan interest rate cost *i* €; $R_{d(i)}$ is the discount factor for the year *i* €.

Renovation measures were assessed based on the difference of NPV (ΔNPV) of the reference case and the renovated case (Eq. 2):

$$\Delta NPV = (C_G - C_G^{ref}) / A_{floor} \qquad \text{Eq. 2}$$

where C_G is the global cost of the building in the renovated case , €; C_G^{ref} is the global cost of the building in the reference case, €; A_{floor} is the heated net floor area of the building, m^2.

The real interest rate was 4% and a 3% annual escalation of energy price was used in the calculations.

The initial investment cost includes construction works and the components related to indoor climate and energy performance measures: additional thermal insulation with finishing, windows, AHUs and heat supply solutions with the required duct and pipe works. The final cost of renovation could be higher if the energy renovation process includes other works. The construction costs were composed of labour costs, material costs, overhead, the share of project management and value added tax.

Prices for the different parts of the construction works were obtained from the construction companies. Discounted energy cost included all annual costs related to heating and electricity energy consumption. The prices for the energy carriers were obtained from the suppliers' data from 2012:

- heating wood (billet): 37.7 €/MWh;
- pellet: 39.6 €/MWh;
- natural gas: 47.4 €/MWh;
- district heating: 68.3 €/MWh;
- electricity: 118.0 €/MWh.

3.3 Indoor climate and hygrothermal loads

To assess the indoor climate (thermal comfort, indoor air quality, hygrothermal loads) in the historic wooden apartment buildings, measurements were conducted in 41 apartments in 29 buildings.

The temperature and RH indoors were measured continuously with HOBO data loggers (Onset Hobo U12-013; measurement range – 30 °C …+70 °C; 5…95% RH, with an accuracy of ±0.35 °C; ±2.5% RH). Temperature and RH inside the bedroom and outside the building were recorded at a one-hour interval. The indoor loggers were located on separating walls in the master bedroom or in the living room and to measure outdoor temperature at the reference measurement points, the loggers were placed on the north facade of the building, protected from direct solar radiation.

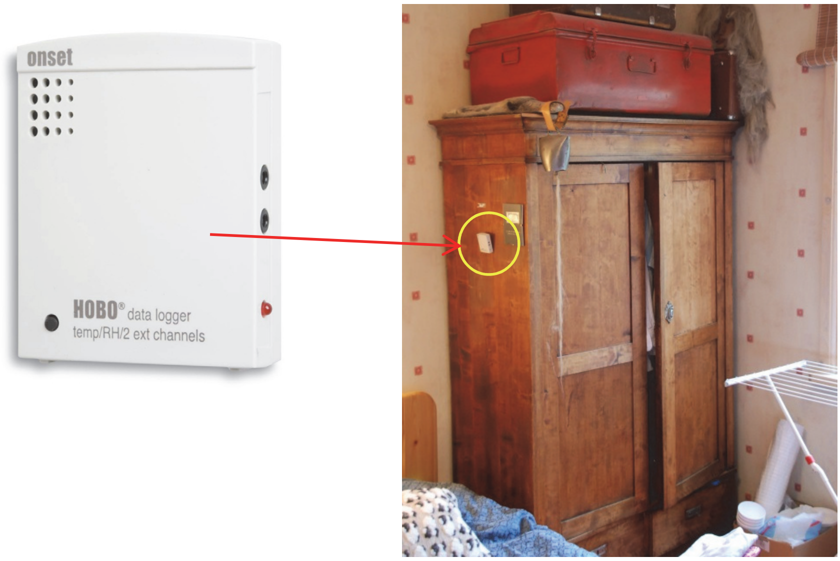


Figure 3.7 Measurement of indoor temperature and RH in a bedroom: used logger (left) and location in bedroom (right).

Target values from the indoor climate category “class III” (CR1752; EN15251) were selected to assess measured indoor thermal conditions. Indoor climate category “class III” represents an acceptable moderate level of expectation used for existing buildings. In the thermal evaluation, an hourly criterion was used, based on the calculation of the percentage of time when the criteria are met or are outside a specified range: +18…25 ºC during winter months and +22…27 ºC during summer months.

For hygrothermal dimensioning of the building envelopes, sufficiently critical humidity loads should be considered. Sanders (1996) has recommended the use of 10% percentile as the critical level. This means that hygrothermal loads higher than their normative value should not appear in more than 10% of the cases.

Another approach would be a stochastic analysis taking into account more realistic conditions.

For the moisture load the moisture excess $\Delta\nu$ (g/m^3) was calculated on the basis of the measured results of the indoor and outdoor temperatures and RH:

$$\Delta\nu = \nu_i - \nu_e = \frac{G}{R_a}, \text{ g/m}^3 \qquad \text{Eq. 3}$$

where ν_i is the indoor air water content, g/m^3; ν_e is the outdoor air water content, g/m^3; G is the moisture production indoors g/h, and R_a is the ventilation and infiltration air flow m^3/h.

To analyse the dependence of the moisture excess on the outdoor climate and to determine the critical moisture excess values, the data were sorted according to the outdoor air temperature, using a 1 ºC step of the outdoor temperature. Using the sorted values, average (avg), maximum (max), minimum (min), standard deviation (st.dev), and 10 % critical levels were calculated.

Thermal conditions, indoor air quality, and hygrothermal conditions in the buildings are strongly influenced by the outdoor air flow rate in the apartments. CO_2 measurements were conducted to assess the indoor air quality and air change in the apartments. CO_2 levels were measured in the bedrooms during the winter and summer periods at 10-minute intervals during 2…3 weeks using Telaire CO_2 monitors with Hobo data loggers (Telaire 7001; measurement range 0…10000 ppm, with an accuracy of ±5% of reading or 50 ppm).

Air change calculations were based on the measurements of indoor CO_2 levels and estimated CO_2 emissions from the inhabitants (Guo & Lewis 2007):

$$C_{i,t} = C_e + \frac{E}{R_a} - \left(C_e + \frac{E}{R_a} - C_{i,0}\right) \cdot e^{-\frac{R_a}{V}\cdot\tau} \qquad \text{Eq. 4}$$

where $C_{i,t}$ is the CO_2 concentration at time "τ", ppm; C_e is the CO_2 concentration of the outdoor air, ppm; E is the CO_2 generation rate (13 l/h·pers); R_a is the ventilation and infiltration air flow, m^3/s, $C_{i,0}$ is CO_2 concentration at the start of the time period, ppm; V is the volume of room, m^3; τ is the time, s. In the calculations, the measurement results from the night time (23:00 – 7:00) were used.

The ventilation air flow rates required are specified as an air change per hour for each room, and/or outside air supply and/or required exhaust rates (bathroom, toilets, and kitchens) or given as an overall required air-change rate in dwelling. According to the indoor climate category "class III", the required overall air-change rate should be 0.5 h^{-1} or 4 l/s per person or 0.6 l/s per area of the bedroom (EN15251).

In addition to the temperature, air sampling of RH and CO_2 measurements was used to assess the contamination of the indoor air by airborne microorganisms. The Biotest HYCON Air sampler RCS was used to take the air samples that were later analysed at the Centre for Materials Research of Tallinn University of Technology. Y and F sampling stripes and 4-minute sample times were used for sample collection. The incubation time was eight days at the temperature 21 ºC for later analysis. No mould species were detected in the incubated air samples. In this study the samples were collected during January and February when the outdoor temperature prevails below 0 ºC and the concentration of the spores in the outdoor air is very low. Our results are expressed as colony forming units (cfu) per volume of air (for air samples): cfu/m^3.

The tape sampling technique was used to identify mould species in the buildings where discoloration of surfaces or mould growth was detected during visual inspection. The samples were taken in kitchens, bedrooms or washing rooms or in living rooms if the mould growth was detected. Adhesive tape lift samples were collected using 3M Crystal Clear Tape and later analysed by the Centre for Materials Research of Tallinn University of Technology.

Singh et al. (2010) have presented the levels recommended in Great Britain that are 200 cfu/m^3 as "low"; 1000 cfu/m^3 as "intermediate" and 10000 cfu/m^3 as "high". Husman et al. (2002) have provided the limits for the quantity of fungal spores in the indoor air used in Finland, which is 500 cfu/m^3. The levels in these two studies differ by an order of magnitude. As the relation between dampness, microbial exposure and health effects cannot be quantified precisely, no quantitative health-based guideline values or thresholds can be recommended for acceptable levels of contamination with microorganisms (WHO 2009). Since there are no limits set in Estonia, the Finnish reference was used in the comparison because of similarities in Estonian and Finnish climate. Concentrations below 500 cfu/m^3 were found to be typical in Finnish buildings without moisture problems in winter. A quantity of fungal spores in the indoor air was compared with the hazard classes presented in the (WHO 2009) guidelines.

In addition, a questionnaire was conducted for each building to obtain information about the occupants' habits, typical complaints and symptoms concerning indoor air quality (Kalamees 2011).

3.4 Hygrothermal performance of a log wall with the interior thermal insulation

3.4.1 Measurements

The hygrothermal performance of interior thermal insulation was measured in a typical apartment in the wooden apartment building referred as "Lender's building" (reference building A, see Figure 3.8), situated in a milieu valuable area in Tallinn. The building originates from the beginning of the 20th century. It was under complete renovation and occupants (who were also owners) decided to insulate exterior walls with mineral wool insulation from the interior side. After discussions, the owners allowed the follow-up measurements to be conducted about the hygrothermal performance of the wall with interior insulation.

Figure 3.8 The building where measurement were conducted before and after the renovation.

The two-floor building had a cellar, and apartments were heated by stove and electrical radiators. There was a natural passive stack ventilation system in apartments with mechanical exhaust fans in the toilets (not permanently used).

The test wall was situated on the north-facing wall of the main bedroom in an apartment on the first floor. The initial log wall construction consisted of a 140 mm log sealed with a tow and exterior side covered with sheathing bitumen paper and 20 mm thick wooden cladding (without air layer). Six different insulation solutions were used. The size of the analysed wall section was 60×60cm. All wall sections faced the same wall of the bedroom. Test walls were separated by metal battens and polyurethane foam tightening. The solutions differed in the insulation materials and air barriers, see Figure 3.9. Three different insulation materials were used:

- reed insulation mat (λ_{reed}≈0.054 W/(K·m)),
- cellulose insulation ($\lambda_{cellulose}$≈0.045 W/(K·m)),
- mineral wool ($\lambda_{min.wool}$≈0.040 W/(K·m)).

Insulation materials were used with and without air barrier and were finished inside the room with gypsum board or render. Air barrier paper impregnated with bitumen (Z_p 0.6·10^9 m·s·Pa/kg) was used as an air barrier between the inside sheathing and the insulation material. Sections of the insulated log wall are shown in Figure 3.10.

Figure 3.9 View of the wall during constructing the test walls construction and temperature and RH sensor positions on the log layer before the insulation material was added (bottom right).

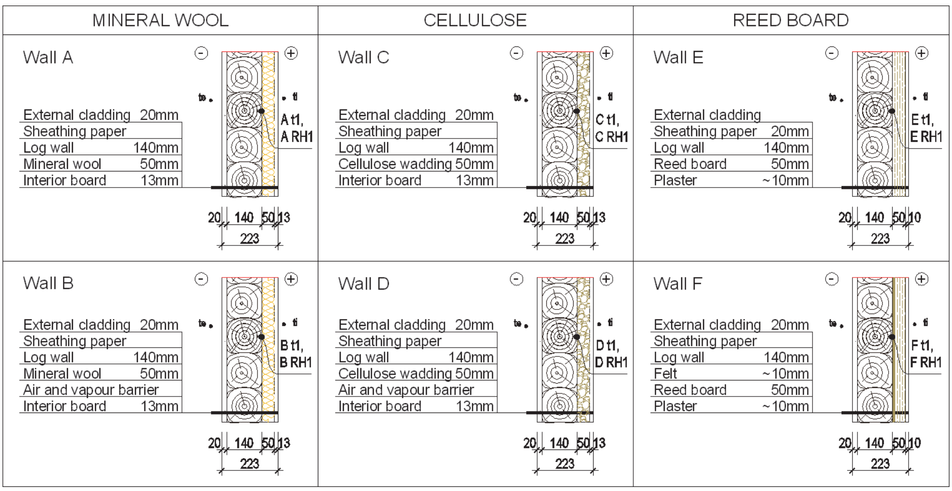


Figure 3.10 Sections of the studied test walls.

The values of temperature and RH inside the wall sections were measured with ∅ 5 mm sensors (Rotronic Hygroclip SC05; measurement range: - 30 °C…+100 °C, 0…100 % RH with accuracy ±0.3 °C, ±1.5 % RH) and saved with a data logger (Squirrel SQ2020). The sensors were installed inside the wall between the additional thermal insulation layer and the log layer (see Figure

3.11). Temperature and RH inside the bedroom and outside the building were measured with data loggers (Hobo U12-013; measurement range - 20…+70 °C; 5…95% RH, with an accuracy of ±0.35 °C; ±2.5% RH). All the measurements were saved at one-hour intervals. The indoor data logger was placed in the middle of the bedroom and an outdoor temperature data logger was placed on the north facade of the building, protected from direct solar radiation.

Figure 3.11 Temperature and relative humidity sensor on the log layer before the insulation material was added.

3.4.2 Simulations

The WufiPro5.1 (WUFI) was selected for the hygrothermal analysis. Comparison of the calculation results against the measurements of wooden structures using the WUFI simulation tool has shown a good correlation in different studies (Kalamees 2003; Hägerstedt 2011; Mundt-Petersen 2015).

The program introduces two potentials for moisture flow: the liquid transport flux depends on RH and the water vapour diffusion flux depends on the vapour pressure. The governing equations employed in the WUFI model for mass and energy transfer are as follows (Künzel et al. 2000):

Moisture transfer:

$$\frac{\partial w}{\partial \varphi} \cdot \frac{\partial \varphi}{\partial t} = \nabla \cdot (D_{\varphi} \nabla \varphi + \delta_p \nabla (\varphi \, p_{sat})) \qquad \text{Eq. 5}$$

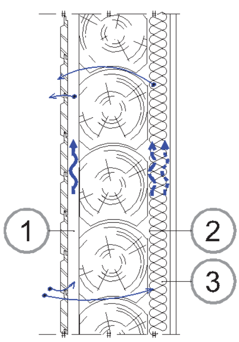
Energy transfer:

$$\frac{\partial H}{\partial T} \cdot \frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) + h_v \nabla \cdot (\delta_p \nabla (\varphi \, p_{sat})) \qquad \text{Eq. 6}$$

where φ is the relative humidity, -; t is time, s;, T is temperature, K; c is specific heat, J/(kg·K); w is moisture content, kg/m^3; p_{sat} is vapour pressure at saturation, Pa; λ is thermal conductivity, W/(m·K); H is total enthalpy, J/m^3; D_{φ} is the liquid conduction coefficient, kg/(m·s); δ_p is vapour permeability, kg/(m·s·Pa); h_v is latent heat of phase change, J/kg.

There is an interaction between water vapour diffusion and liquid transport in building components (Künzel 1995). Depending on the gradients of vapour pressure and relative humidity, the moisture flow can run in the same or in the opposite directions. For example, in cold climate under winter conditions the vapour pressure is higher inside than on the outside of the building due to the temperature difference. The vapour diffusion takes place from the inside to the outside. Usually, the relative humidity is higher outside than inside; thus the gradient of relative humidity runs the water content into the opposite direction. The phenomenon described introduces some error into the calculations if the material properties are described only using water vapour diffusion resistance factor or moisture diffusivity in the simulation model.

The detailed airflow through the structure is not considered in the assessment of moisture behaviour. Thus, the model allows a transient consideration of the convective moisture sources depending on the specific air permeance of the component, on the height of the connected airspace, on the selection of the potential condensation layer within the building component and on the transient exterior and interior climate conditions (Künzel 2012). Simplified vapour infiltration model was used to take into account air change between material layers and indoor or outdoor air. The air flow can be added as the air change rate. The air in the material layer is mixed with outdoor air or indoor air. An assumption was made that moisture flow can be affected by convection. The convection can be caused by the temperature difference or by wind. The convective flow was entered as the air change source in the material layers on both sides of the existing log layer. An assumption was made that the new material layers added inside the room are more air tight than the existing log layer and external cladding. So the air inside the wall is mixed with the outdoor air. An air change source described in the simulation model is shown in Figure 3.12.



Position	Air change rate [1/h]
1 between external cladding and log layer	2,5
2 between insulation and log layer (5mm insulation layer)	2,0
3 inside insulation material (45mm insulation layer)	0,5

Figure 3.12 Air change source between the material layers.

Rough estimation of the air change rate was based on the studies of Vinha (2007); Künzel (2011); Kehl (2011); Hägerstedt (2011). The final air change rates used in the simulation models were 2.5 h^{-1} between the external cladding and the existing log layer, 2 h^{-1} (0.5 m/s) inside the 5 mm thick insulation layer, and 0.5 h^{-1} (0.2 m/s) in the rest of the insulation layer on the internal side of the log layer.

WUFI contains a large material database from different sources. In addition to basic constant data (bulk density, porosity, specific heat capacity of dry material, thermal conductivity of dry material, water vapour diffusion resistance factor of dry material), WUFI database includes also some moisture-dependent properties: moisture storage function w, kg/m^3; liquid transport coefficient for suction D_{ws} and for redistribution D_{ww}, m^2/s; thermal conductivity λ, W/(m·K); vapour diffusion resistance factor μ, -.

D_{ws} describes the capillary uptake of water when the imbibing surface is fully wetted. D_{ww} describes the speed of distribution of imbibed water when wetting is finished. As soon as the water is removed from the suction surface, the field of capillary pressures changes to a new equilibrium. Redistribution is dominated by the smaller capillaries since their higher capillary tension draws the water out of the larger capillaries. Since redistribution is a slower process than suction, the moisture diffusivity for redistribution generally is markedly lower than moisture diffusivity. Depending on the material, this redistribution can be 3 to 20 times slower than absorption, typically about one tenth (Krus 1996; Künzel et al. 2000).

Because the measurement results showed high humidity level inside the wall during the whole measurement period, in addition to water vapour flow, the water flow in liquid form was also present. Therefore, material properties were described considering both moisture flows: vapour diffusion and liquid transport. Both properties depend on the moisture content of the material. Four theoretical cases were calculated to acquire a better understanding about the relationship between material properties and diffusive and capillary moisture flow in the wall. In the first case, case “W”, the material properties were used as described in the material database, both moisture-dependent. In the next two cases, “X” and “Y”, the water vapour diffusion resistance factor was set as constant. In the last case, “Z”, the simulation was done excluding a capillary flow. The influence of the material properties on the total moisture flow is presented in Figure 3.13

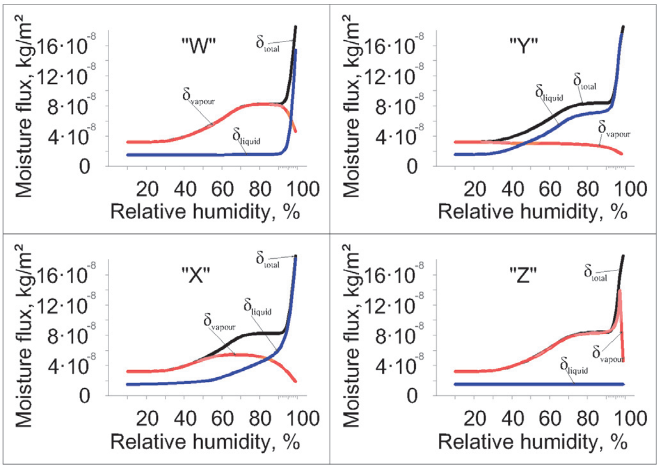


Figure 3.13 Total moisture flux in the middle of the material in different descriptions of water vapour δ_{vapour} and liquid water δ_{liquid}.

Material properties affecting the speed of liquid moisture transport are liquid transfer coefficients. The effect of capillary flow may have a significant impact on the simulation results depending on the materials. In case the material properties were used as described in the material database, both moisture-dependent, the capillary flow starts to have an impact on the moisture flux on higher RH levels than 95%. The results of simulation tests on external walls with a capillary flow are presented by (Vinha 2007). If vapour resistance changed significantly already in the hygroscopic range, the capillary flow was set to start affecting the materials when the value of water resistance started to diminish (Vinha 2007).

The liquid transfer coefficient of the library material was compared with the moisture diffusivity values presented in the literature. The results of different tests and the variability of the values are presented by Time (1998; Kumaran (1996); Kumaran (2002); Krus & Vik (1999); Sonderegger et al. (2011). The comparison between the moisture diffusivity of the library material data and results presented in the literature show the difference of about two orders of magnitude. The material properties of the wood layer in the simulation model were changed according to the difference, the liquid transport coefficient for suction and the liquid transport coefficient for redistribution were multiplied by 100. The modified materials were used to describe the log layer of the walls.

The simulations were done using a modified material. The properties of different materials used in the simulation models are presented in Table 3.5.

Table 3.5 Material hygric properties in the simulation models

Material properties	RH, %	Gypsum board	Mineral wool	Cellulose wadding	Reed insul. Mat	Wood (spruce)	Bitumen paper
Bulk density ρ, kg/m^3		574	60	60	136	390	130
Porosity ξ, m^3/m^3		0.77	0.95	0.95	0.9	0.75	0.001
Water vapour diff. resistance factor μ, -	35	7.7	1.3	1.5	2	108	100
	55	7.0	1.3	1.5	2	39	
	75	6.5	1.3	1.5	2	27	
	100	6.0	1.3	1.5	2	27	
Thermal conductivity λ, W/(m·K)		0.19	0.045	0.06	0.065	0.13	-
Moisture content w, (kg/m^3)	33	2.4	-	3.4	5.2	27.3	-
	55	5.1		4.9	6.3	37.1	
	97	7.2		24.6	36.2	81.9	
	100	17.7		570	600	600	
Liquid Transport D_{ws}, (m^2/s)	33	$2.9\cdot10^{-12}$	-	$76\cdot10^{-12}$	$6.2\cdot10^{-11}$	$4.4\cdot10^{-11}$	-
	55	$1.5\cdot10^{-11}$		$11\cdot10^{-11}$	$8.1\cdot10^{-11}$	$5.9\cdot10^{-11}$	
	97	$2.2\cdot10^{-10}$		$22\cdot10^{-10}$	$9.7\cdot10^{-10}$	$1.3\cdot10^{-10}$	
	100	$1.6\cdot10^{-7}$		$45\cdot10^{-8}$	$5.2\cdot10^{-8}$	$9.2\cdot10^{-10}$	
Liquid Transport D_{ww}, (m^2/s)	33	$2.9\cdot10^{-13}$	-	$7.5\cdot10^{-13}$	$6.2\cdot10^{-12}$	$4.4\cdot10^{-11}$	-
	55	$1.5\cdot10^{-12}$		$1.4\cdot10^{-12}$	$8.1\cdot10^{-12}$	$5.9\cdot10^{-11}$	
	97	$2.2\cdot10^{-11}$		$2.2\cdot10^{-11}$	$9.7\cdot10^{-11}$	$1.3\cdot10^{-10}$	
	100	$1.6\cdot10^{-8}$		$4.9\cdot10^{-9}$	$5.2\cdot10^{-9}$	$9.2\cdot10^{-10}$	

The boundary conditions of the exterior and interior surface of the wall were calculated using temperature and RH measurement results to eliminate the effect of surface transfer coefficients. The internal surface RH was calculated by changing the water vapour pressure at saturation according to the measured temperature on the surface of the wall.

3.4.3 Assessment of the hygrothermal performance

According to (Hukka & Viitanen 1999, Ojanen et al. 2010; Viitanen et al. 2011), the risk of mould growth covers the temperature range of 5-40 °C; the boundary curve for the risk of mould growth on a wooden material can be described by a polynomial function:

$$RH_{crit} = \begin{cases} -0.00267\cdot t^3 + 0.160\cdot t^2 - 3.13\cdot t + 100 & ,when\ t \le 20°C \\ 80\% & ,when\ t > 20°C \end{cases} \qquad \text{Eq. 7}$$

Expected risk and durability of materials to mould growth can be predicted by calculating the mould index (*M index*) (Viitanen et. al. 2011) using the dynamic temperature and relative humidity histories of the subjected material surfaces.

M index describes the mould growth rate and the visual appearance of the mould on the material surface as follows:

- 0: no growth;
- 1: small amounts of mould on surface (microscope), initial stages of local growth;
- 2: several local mould growth colonies on surface (microscope);
- 3: visual findings of mould on surface, <10% coverage, or, <50% coverage of mould (microscope);
- 4: visual findings of mould on surface, 10 – 50% coverage, or, >50% coverage of mould (microscope);
- 5: plenty of growth on surface, >50% coverage (visual);
- 6: very heavy and tight growth, coverage about 100%.

The moisture safety of the interior insulation as a retrofit measure in a historic wooden building was analysed using a stochastic approach. The outdoor climate conditions, indoor climate loads, different retrofitted wall assemblies and quality of workmanship were used as the varying input data parameters. A base case for the performance analysis is the wall assembly with the design values and with the average indoor temperature and average moisture excess (Figure 3.14).

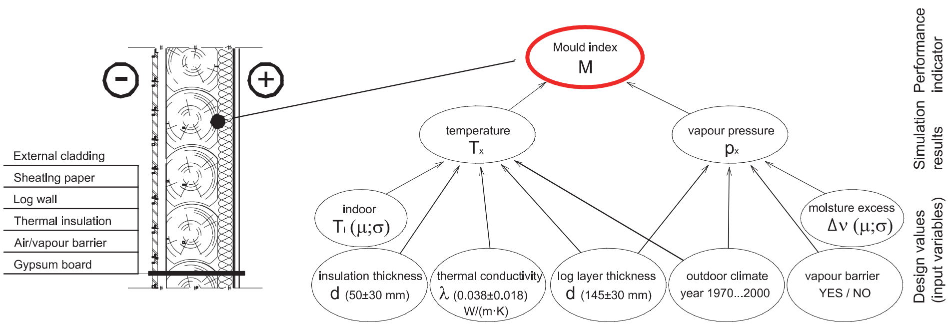


Figure 3.14 Design variables for the hygrothermal simulation model.

For the outdoor climate conditions, measured data obtained from Estonian Weather Service (EWS) for 30 years (from 1970 to 2000) were used for the simulations. Indoor climate conditions were simulated using the indoor hygrothermal load model for stochastic analyses presented in (II).

Uncertainty and variations in the distribution prevail in all the input data. The Monte Carlo method was used for sampling input variables according to their probabilistic characteristics: t_i and Δv are described by normal distribution; λ of insulation material, insulation material thickness and log layer thickness were uniformly distributed; the vapour barrier (bitumen impregnated paper S_d=0.18 m,

Z_p=0.96 (m^2·s·Pa)/kg Vinha (2005)) was considered as installed or not (yes or no; for example, no means also the situations when vapour barrier is broken during construction works by installations).

Each input value was randomly selected according to the distribution, altogether 100 combinations were generated and each combination represents an individual simulation.

In the first step of the analysis for randomly generated simulation cases, the temperature and RH conditions inside the wall were simulated using the calibrated WUFI model (VI) and the *M index* was calculated for all simulated cases.

In the second step, the logistic regression analysis was used to estimate failure probability depending on different variables. The WUFI simulations and the statistical computing environment R were used to calculate the logistic regression coefficients. For each variable, three values were selected (−1; 0; 1), for variables with normal distribution, avg ±standard deviation values were applied, for variables with uniform distribution avg, min and max values were used, and for the vapour barrier, YES or NO was selected. For the regression coefficient calculations, a total of 486 combinations were generated. For every combination, a WUFI simulation was performed and *M index* was calculated to check whether an unwanted outcome occurs or not. The unwanted outcome is indicated as *M index* >1.

After the regression coefficient calculation, the probability for 100 combinations generated in the first step were calculated as follows:

$$p = \frac{e^{(\alpha+\beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \ldots + \beta_n x_n)}}{1 + e^{(\alpha+\beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \ldots + \beta_n x_n)}} \quad \text{Eq. 8}$$

where p is a probability that a case is in a particular category (*M index* > 1), e is the base of natural logarithms, α is the constant of the equation, and β_i is the coefficients of the predictor variables x.

The Spearman correlation (Spearman Rho) was used to evaluate the correlation between *M index* values (randomly generated simulation cases) calculated in the first step and probabilities (based on the regression coefficients) calculated in the second step.

3.5 Assessment of the milieu values during the renovation process

First, in each renovation process, the need for renovation and the assessment criteria for renovation measures must be defined. The need for renovation can be viewed from the following aspects:

A. Urgent repairs to guarantee safety of buildings (mechanical resistance and stability, safety in use, safety in case of fire);

B. Improvement of indoor climate (hygiene and health aspects, fulfilment of requirements to ventilation air rates and room temperatures; protection against noise);
C. Improvement of energy performance of a building as well as sustainable use of natural sources;
D. Improvement of architectural planning, visual quality, overall living quality, and additional comfort.

Safety aspects (A) and requirements for indoor climate (B) are usually defined well in legislation and decrees. Usually these are mandatory to fulfil without large deviation. National legislation based on the Energy Performance of Buildings Directive (EU-Directive 2010/31/EU) sets common targets for the energy performance of buildings (C). Even directives and national legislation give exceptions for buildings with special architectural or historical merit, owners and inhabitants have increased interest and willingness to invest in energy saving solutions to decrease expenses for energy, to make renovation more cost effective and to live in a more environmentally friendly building. Life cycle cost optimisation analysis can be used in the assessment of energy renovation measures. The indoor climate and energy audits show the need of improvement of indoor climate and energy performance of a building. Measurements of indoor air quality and thermal comfort in selected apartments could give an overview about the need to improve the indoor climate. The energy audit is specially needed when partial renovation is planned. For deep renovation of a whole building, the pre-renovation energy consumption is rarely required, for example, only when the relative decrease of energy is important to know. Human requirements and needs (D) can change over time and cause also a need for renovation.

Table 3.6 shows how and to what extent the method was used to take into account all the different aspects for the assessment of the energy renovation measures in a historic wooden apartment building.

Table 3.6 Determination of the current situation and renovation solutions

	Topic	Target	Basis of current study
A	Technical condition and need for renovation of wooden apartment buildings	Fulfilment of essential requirements on the performance criteria of the building	The deep technical survey of 29 apartment buildings; the overall technical state and the most common areas requiring improvement are based on a survey of 133 apartment buildings in four towns.
B	Indoor climate	The current state and need for improvement of indoor climate	Measurements of indoor temperature and relative humidity, air change rate, air quality and user satisfaction
C	Solutions for energy economic renovation	The influence of single renovation measures and renovation packages on the use of energy	Measurement of energy use before renovation in 29 buildings and calculations of energy economic renovation of four typical apartment buildings; insulation solutions to improve energy efficiency and thermal comfort
	Values and valuable details of building	Determination of values to be saved and improved; possible changes as well as their influence on the heritage value	The survey of wooden apartment buildings; inquiry about the milieu valuable buildings and how different people perceive the milieu valuable areas and values concerning buildings

To assess the influence of energy renovation measures on the milieu values, the values of external appearance of the buildings were defined. Values were defined by an inventory of renovated building, including the districts where the building is located and similar buildings in other districts through external appearance, details of structures, materials, profile of boarding, colouring etc.

Methodologically, assessment of heritage values is a complex process since subjective evaluations cannot be ruled out entirely. Commonly, a wide range of qualitative methodological approaches are used to assess the heritage values. The conservation field has traditionally relied on expert appraisals (de la Torre 2002). In the current study, subjective evaluations also rely on an expert assessment in cooperation with a conservation specialist from Estonian Art Academy.

In the current study, a replica of an original solution is considered to be acceptable, assuming that construction works follow the best practice. If an assumption is made that additional thermal insulation on the exterior of the building and replica of the original cladding are allowed, then the focus is on the junctions of the building constructions (wall and window; wall and roof; external wall and basement wall). Many onsite measurements were conducted to set the limits for different junctions' protrude and retreat to define the characteristics of the buildings.

The influence of single renovation measures on the appearance of the building is graded based on the following scale:

- 0 – no influence
- -1 – undetectable influence
- -3 – tolerable influence
- -5 – strong negative influence
- -7 – intolerable influence

It is essential to define also the influence of possible differences on the original and on the best solution. The condition of the building before the renovation has an influences on the change of the architectural appearance. If the building is well preserved in view of original materials and details, the influence of the retrofit measure is different from the building with inappropriate changes and lost original details during past times. Therefore, the influences of the retrofit measures have to be assessed taking into account the change compared to the starting conditions of the buildings. The starting conditions are graded based on the following scale:

- 1 – original façade with preserved details
- -1 – typical condition
- -3 – not original old façade, with inappropriate changes

Under different scales, the influence of the retrofit measures can have a positive, neutral or a negative effect. For example, a positive effect implies that the original external appearance is restored: unsuitable cladding is replaced with the replica of historic cladding and with original detailing. A neutral effect implies that the original external appearance is restored without replacement of materials or changes of colours. A minor negative influence (Figure 3.15, b) means that some building elements have been replaced for similar but modern ones. For example, old damaged and leaky windows have been replaced with new and energy efficient windows and installed in their original place. Slightly stronger influence (Figure 3.15, c) on the milieu of the district is observed if the relationships between different structures and building elements change.

A. Original materials, appearance, structure, details and relationships of building elements influence on the milieu value of the district;
B. Change of windows: minor influence on the appearance and milieu value of the district;
C. Additional thermal insulation on the walls up to 50 mm + sheathing (windows step back up to 70 mm; minimum basement wall's step forward): some influence on the appearance and milieu value of the district;
D. Change of windows and additional thermal insulation on the walls, windows moved outward: minor influence on the appearance and milieu value of the district.

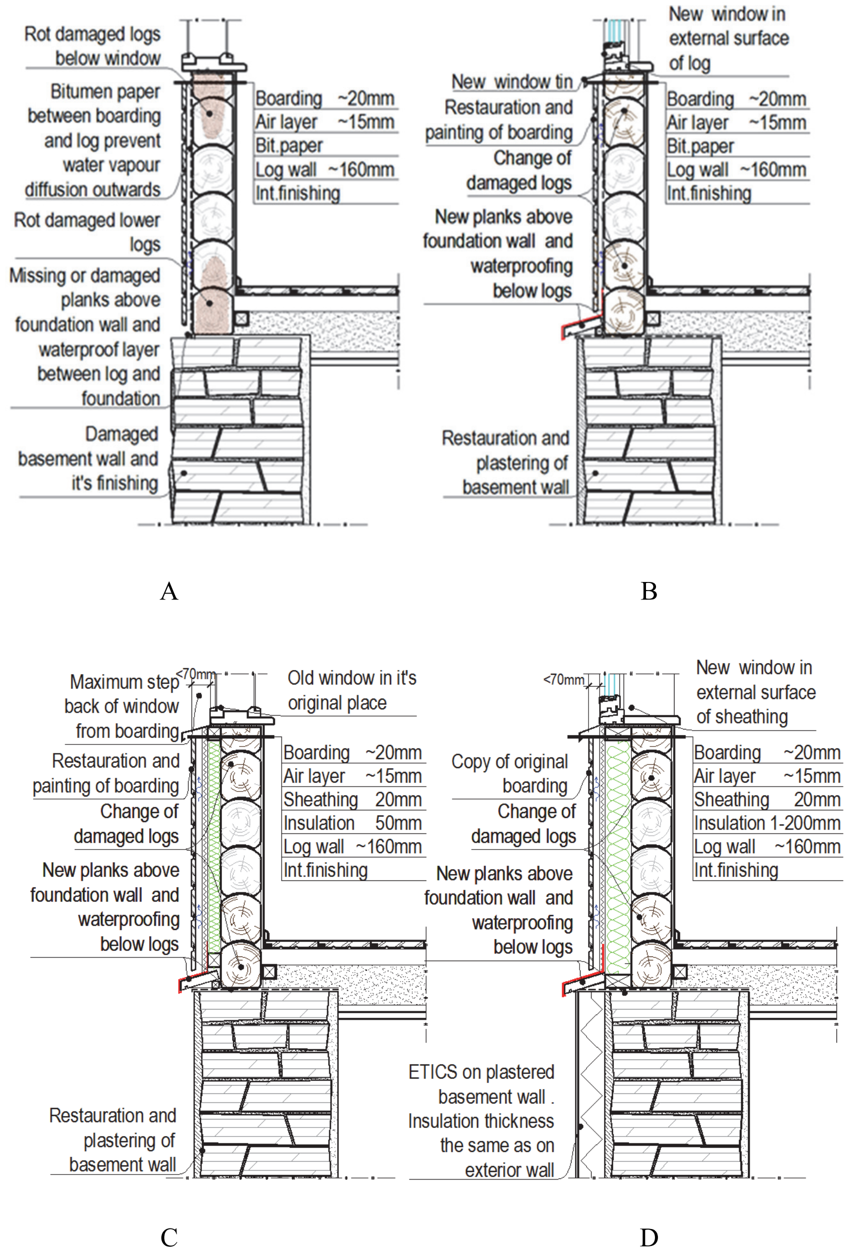


Figure 3.15 Different energy renovation measures and their influence on the architectural appearance.

The usability of the assessment method was tested on a milieu valuable district of historic wooden apartment buildings in Tallinn: "Lender's building"-type wooden apartment building (Reference building "A", see Figure 3.8). In 2010, the case-study building was awarded the title of the best renovated apartment building in a milieu valuable area in Tallinn.

4 RESULTS

4.1 Indoor climate

4.1.1 Indoor climate and hygrothermal loads

To study indoor climate conditions and hygrothermal loads, the dependency of the indoor temperature and moisture excess on the outdoor temperature was analysed. The thin solid lines in Figure 4.1 show the dependency of the average indoor temperature (Figure 4.1 left) and moisture excess (Figure 4.1 right) on the outdoor temperature in one apartment, the dotted curve shows the average of all apartments, and the triangular curve shows the 90% and 10% percentiles of all the apartments.

The average indoor temperature during the winter period was +21.0 (st.dev. 2.3 ºC, min +13.3 ºC and max +24.8 ºC) and during the summer period +24.5 (st.dev. 1.1 ºC, min +22.7 ºC and max +26.7 ºC). During winter the indoor temperature was outside class III (EN 15251) target values in 83% of the apartments and during summer in 25% of the apartments. Throughout the year the indoor temperature was below the target values on average for 80% of time in three winter months and for 1% of time in three summer months, and was above the target values on average for 16% of time in winter and for 2% of time in summer.

The diurnal moisture excess during the cold period (t_e≤+5 C) was +3.3 g/m^3 (st.dev. 1.1 g/m^3) and during the warm period (t_e≥+15 ºC) it was +0.6 g/m^3 (st.dev. 0.7 g/m^3). The average of 90% percentile from the diurnal moisture excess during the cold period was +5.1 g/m^3 and during the remaining time +3.0 g/m^3. Weekly average moisture excess values were: +3.0 g/m^3 (st.dev. 1.1 g/m^3); +0.7 g/m^3 (st.dev. 0.7 g/m^3); average of 90% percentile +4.3 g/m^3 and +1.9 g/m^3, respectively.

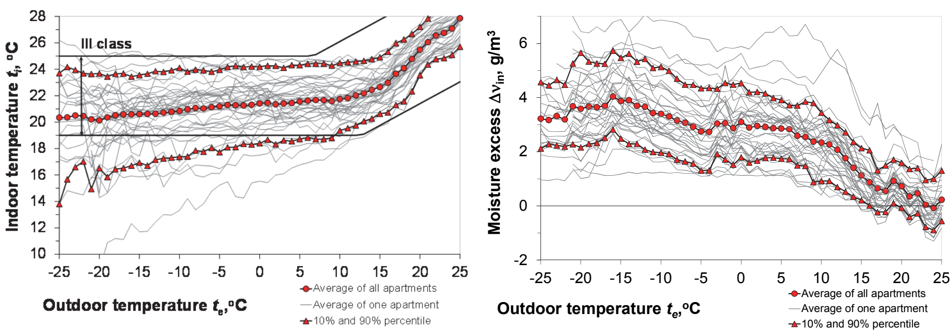


Figure 4.1 The dependency of indoor temperature (left) and moisture excess (right) measurement results on the outdoor temperature.

From the measurement results, a temperature and humidity load model for hygrothermal design was derived. Indoor temperatures show a turning point at the outdoor temperature of +15 ºC. The average indoor temperature curve rises from +20 ºC to +22 ºC during the heating season when outdoor temperatures range from -25 ºC to +15 ºC. After the outdoor temperature level +15 ºC, the incline of the curve is steeper and it rises from +22 ºC up to +28 ºC.

The moisture excess curve shows turning points at the outdoor temperatures +5 ºC and +20 ºC. During the cold period ($t_e \leq$+5°C), the average moisture excess curve stays at the level of +3.3 g/m^3 and during the warmer period ($t_e \geq$ +20 ºC) at the level of +0.6 g/m^3. The moisture excess curve shows a linear change between the turning points at the outdoor temperatures +5 ºC and +20 ºC.

The dependency of the standard deviation on the outdoor temperatures describes variations in the average values. In the stochastic analyses, the distribution of values is needed. The difference demonstrates possible variations in occupant habits on the one hand and the differences in the heating capacities and thermal resistance on the other hand. In contrast, the indoor temperature standard deviation curve remains opposite in relation to the indoor temperature. The standard deviation shows a linear correlation on the outdoor temperature, the curve declines from the value 3.5 ºC at t_e -25 ºC to the value 1.5 at t_e +25 ºC. Standard deviations of moisture excess show a linear correlation on the outdoor temperature; the curve declines from the value 1.2 g/m^3 at the outdoor temperatures -25 ºC to +5 ºC and declines to the value 1.5 g/m^3 at t_e +25 ºC. The indoor temperature and moisture load design curves for the historic wooden apartment buildings presented in Figure 4.2 are described by Eqs. 9 to 12.

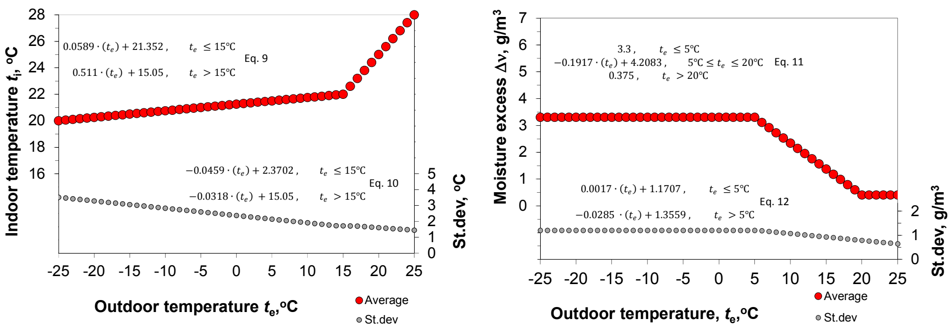


Figure 4.2 Indoor temperature (left) and moisture load design curves for historic wooden apartment buildings.

Thin solid curves in Figure 4.3 (left) show the dependency of an average daily indoor RH on the outdoor temperature and the dotted curve indicates the average RH from all the apartments. The triangular curve represents 10% higher and lower levels of the RH from all apartments.

The indoor RH was calculated with the indoor temperature and moisture excess models to test the conformity of indoor RH conditions to those in reality. Indoor RH was calculated for the number of cases equal to the number of apartments where the indoor climate was measured. Indoor RH was calculated by a model using random sampling. First, the average indoor temperature (t_i) and moisture excess (Δv) with standard deviations (σ_{ti}, $\sigma_{\Delta v}$) were calculated by Eqs.9 to 12 according to the outdoor temperature (t_e). In the next step, assuming normal distribution and using the average values and standard deviations, random sampling was done. Knowing the outdoor RH and temperature, indoor air vapour content was calculated using Eq. 3. The indoor RH was calculated using the indoor air vapour content and saturation content at the corresponding indoor temperature. In the last step, the calculated values of indoor RH and indoor temperature were averaged using a 24-hour running average.

The square curve in Figure 4.3 left presents measured indoor RH and shows good agreement with calculated indoor RH values. Figure 4.3 right compares the cumulative distributions of the measured and the calculated results from five outdoor temperatures (-25 ºC, -10 ºC, ±0 ºC, +5 ºC, and +15 ºC). Even at good agreement between the measured and the calculated RH values, the calculated results show slightly larger aberrancy at higher outdoor temperatures. Generally, the calculated RH levels are higher than the measured RH levels at an equal number of calculated and measured values.

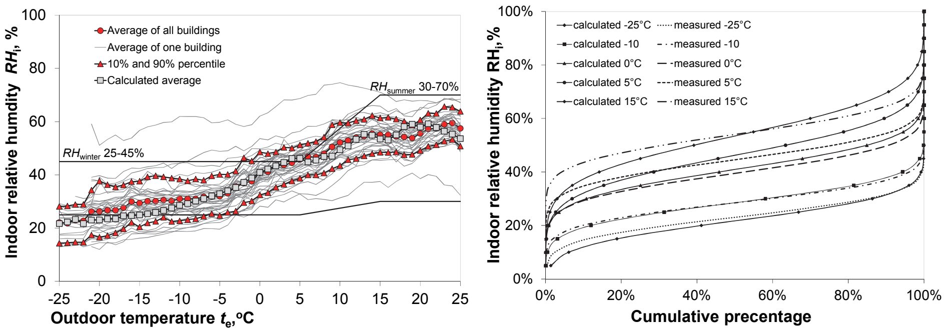


Figure 4.3 Indoor air RH measurement results (left) and comparison of measured and calculated RH (right) at different outdoor temperatures.

Another possibility to present indoor humidity loads is through the indoor moisture production and the ventilation rate Eq. 3. During winter the average ventilation airflow in the bedrooms was 0.43 $l/(s \cdot m^2)$ (varied between 0.1…1.5 $l/(s \cdot m^2)$), and the average air-change rate in the bedrooms was 0.56 h^{-1} (varied between 0.1…2.0 h^{-1}) (Figure 4.4). During summer the average air-change rate in bedrooms was 0.79 h^{-1} (varied between 0.1…2.2 h^{-1}). According to the climate category “class III”, the average air-change rate satisfies the target value. The minimum required air change is fulfilled in 44% of the bedrooms. In terms of airflow per floor area in the bedrooms, only 26% of them complied with the target value of the climate category “class III”.

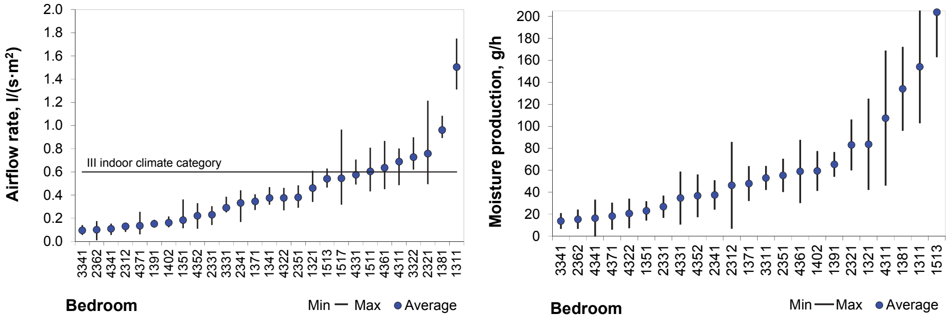


Figure 4.4 Airflow rate (left) and moisture production (right) in bedrooms during winter period.

Average moisture production in the bedrooms during night was 60 g/h (variation between 14…200 g/h). The moisture production calculated shows mainly moisture from inhabitants as the ventilation airflow rate, and moisture excess values are measured during the night time. These values indicate moisture production from common household activities. This value includes also moisture transport between room air and building fabric. Presented moisture production values can be used as input values for the indoor climate of a whole building and energy simulation programs targeted to moisture transfer between the room air and the building fabric are neglected. When advanced numerical hygrothermal tools are used in the simulation programs covering the whole building and the moisture transfer between the room air and the building fabric is taken into account, the corresponding moisture production value should be larger. Based on moisture buffering studies (Svenberg et al. 2004, Rode & Grau 2008), moisture buffering mainly influences daily variations in the range from 10% to 40%, depending on the furnishing and building fabric.

4.1.2 Indoor air quality

Indoor CO_2 concentrations were used as an indicator of indoor air quality since occupants are the main pollution source in dwellings. During measurements, the peak values varied between 1287 ppm to 3999 ppm in the winter time. During the winter period, the average value of all the bedrooms (occupied) was 1084 ppm (varied between 537…1972 ppm) in the night time. During the summer period, the average value of all the bedrooms was 1062 ppm (varied between 614…1565 ppm). Measured CO_2 concentrations were above 1000 ppm for 51% of the measurement time during the winter period and for 45% of the measurement time during the summer period. Measured CO_2 concentrations were above 1500 ppm for 18% of the measurement time during winter and summer periods.

Different species of fungi found in the tape lift samples are presented in Table 4.1. The largest numbers of spores found in the indoor air were *Cladosporium* and *Phoma*. The spores most frequently found in the apartments are the spores with the highest health risk (Singh 2000). The number of spores in the indoor air need not be very high to cause health problems.

Table 4.1 Occurrence of different species of fungal spores found in tape lift samples

Finding	% of occurrence
Chaetomoium	2
Cladorrhinum	2
Cladosporium	13
Echinobotryum sp.	2
Epicoccum	2
Exophiala	3
Phoma	10
Ulocladium	3
spores with no ID	10
mycelioum with no ID	3
no spores (soot, dust)	50
Total number of samples	100

No relevant correlation (low R^2) was found between the quantity of spores in the indoor air and the average indoor temperature in the apartments. Relevance in relation to the mould growth is higher in the indoor RH (moisture excess, moisture production) and air change rate (ventilation, air tightness) in the apartments. But the trend indicated is - the higher the moisture excess, the higher the RH and the higher is the number of spores in the indoor air. The average moisture excess over 6 g/m^3 and the RH over 60% show that the quantity of spores in the indoor air is higher than the acceptable level 500 cfu/m^3, Figure 4.5.

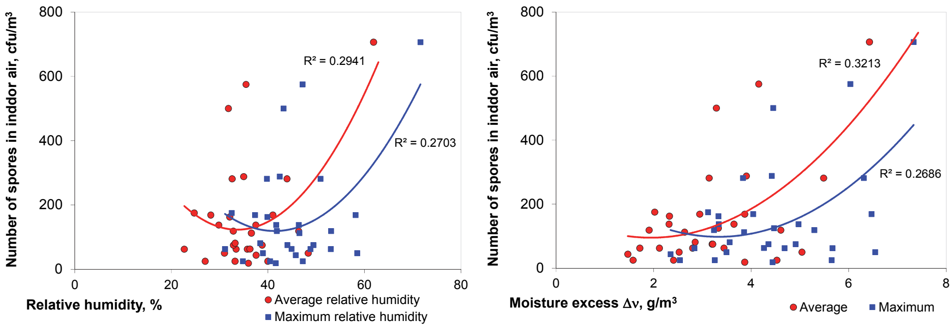


Figure 4.5 The dependency of the number of spores in indoor air on the indoor air RH (left) and moisture excess (right).

4.1.3 User satisfaction

A questionnaire was conducted in each building to survey occupants' habits, typical complaints and symptoms concerning the indoor air quality. To ensure reasonable data collection about the inhabitants' opinion, in a simple context, the questions concerned seriousness and the frequency of the problems. Due to the cold outdoor climate, most of the questions were targeted to the indoor conditions during the heating period when the heating and ventilation systems are of critical importance. The main problems indicated by the inhabitants were unstable temperature, cold floors and stuffy air during the winter period. The occurrence and frequency of the main problems are presented in Figure 4.6.

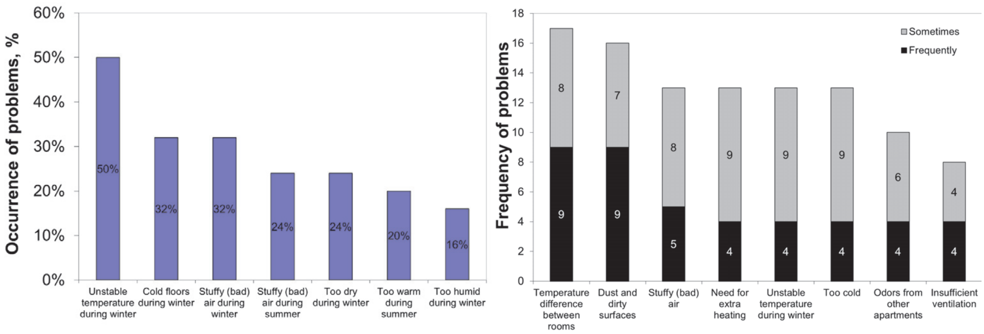


Figure 4.6 Occurrence (left) and frequency (right) of the problems based on the questionnaire.

Occupants' responses were used to find relations between the measured indoor climate parameters and the inhabitants' complaints. Despite the fact that the average temperature in most of the buildings was on an acceptable level, inhabitants complained about the unstable indoor temperature. Complaints can be explained by the indoor temperature prevailing outside the target levels and also by diurnal temperature variations.

When the inhabitants complained about the unstable temperature during the winter time, the average daily temperature variation was 3.8 ºC ; it was 1 ºC higher than in the buildings with no complaints (p=0.045). Also, periods with the indoor temperature outside the target levels were 26% greater. Results of the survey showed that complaints about the indoor temperature composed 42% and absence of complaints 16% of the time, which is incompliance with the indoor climate class III. Problems with cold floors during winter (p=0.019) occurred in apartments with unstable temperature. The reason is likely to lie in the infiltration and low thermal resistance of the constructions or in insufficient power of the heating system. Buildings with larger temperature variations and cold floors during winter were much leakier, at higher air-change rate n_{50} (p=0.036) and had larger energy consumption (p=0.047) than buildings with no occupants' complaints.

4.2 Energy performance and energy saving potential

4.2.1 Energy use of the historic wooden apartment buildings

To give an overview of the real energy use in historic wooden apartment buildings in Estonia, the energy consumption of the buildings was analysed based on the measured data collected in 29 buildings.

The overall electricity use includes lighting, electric appliances, domestic hot water and in some buildings also space heating. In the studied buildings, the annual average of overall electricity use was 58 kWh/(m^2·a) with a minimum of 27 kWh/(m^2·a) and a maximum of 107 kWh/(m^2·a). Because of electricity use for hot water heating in most cases and for heating in some cases, the average electricity usage was above 30 kWh/(m^2·a) that represents electricity use in standard conditions (Ordinance No. 63 2012) and was used as indoor heat gain in energy performance calculations.

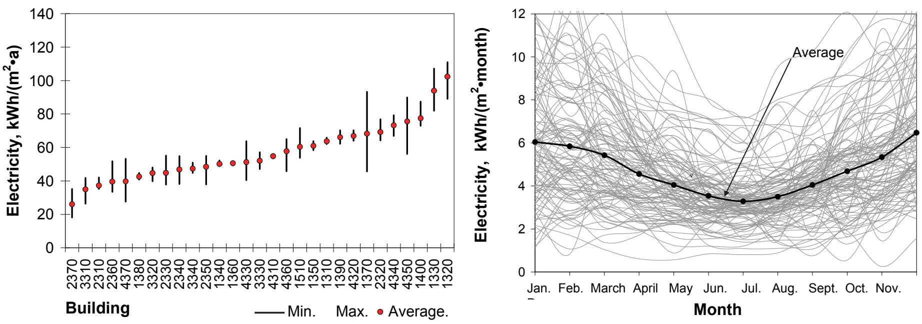


Figure 4.7 The average annual (left) and monthly (right) use of electricity in studied wooden apartment buildings.

The annual total water usage was 986 l/(m^2·a) (st.dev. 329 l/(m^2·d)) and 72 l/(pers·d) (st.dev. 21 l/(pers·d)). The domestic hot water usage was 410 l/m^2·a (st.dev. 130 l/m^2·a), which is 40% (Kõiv 2005) of the total water consumption. The annual average energy usage for domestic hot water heating was 36 kWh/(m^2·a) (st.dev. 11 kWh/(m^2·a)), taking into consideration that water is heated up from 5 ºC to 55 ºC.

Gas was used for space heating, for domestic hot water and for cooking. The overall annual average usage of gas was 16.3 m^3/(m^2·a) (st.dev. 9.3 m^3/(m^2·a)). Average consumption of gas was 21.6 m^3/(m^2·a) in buildings where gas was used for the domestic hot water and room heating system.

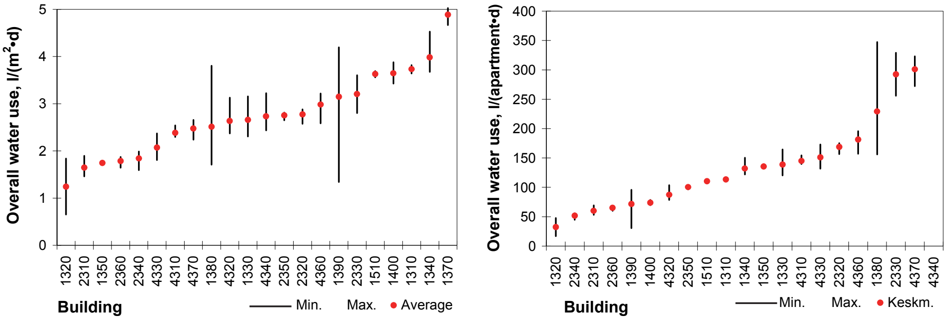


Figure 4.8 The daily average overall (hot and cold) water use in wooden apartment buildings.

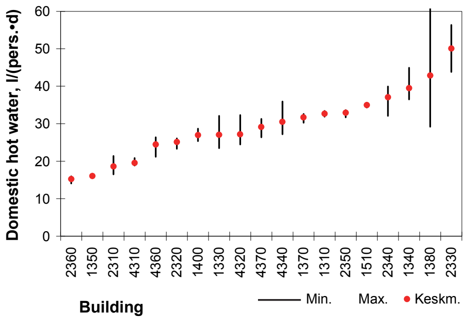


Figure 4.9 The daily average use of domestic hot water in wooden apartment buildings.

The average heating energy used was 211 kWh/(m^2·a) (st.dev. 68 kWh/(m^2·a)) adjusted to the reference year based on HDD at a balance temperature of +17ºC. The energy consumption was calculated using the calorific values 9.3 kWh/m^3 for natural gas, 1300 kWh/(stack m^3) for firewood, 4.6 kWh/kg for wood briquette and 4.2 kWh/kg for peat briquette.

The total primary energy consumption includes the heat and fuel consumption for heating, air change and infiltration, domestic hot water as well the electricity for lighting, electrical appliances and technical systems. The average primary energy consumption was 331 kWh/(m^2·a) (st.dev. 72 kWh/(m^2·a)), Figure 4.10 left. From the studied buildings, 60% fulfilled the requirements for the EPC class “G” (9 buildings), 27% for class “F” (4 buildings) and 13% for class “E” (2 buildings). The average distribution of energy was 50% for heating, 36% for electricity (lighting, electric appliances) and 14% for domestic hot water, Figure 4.10 right.

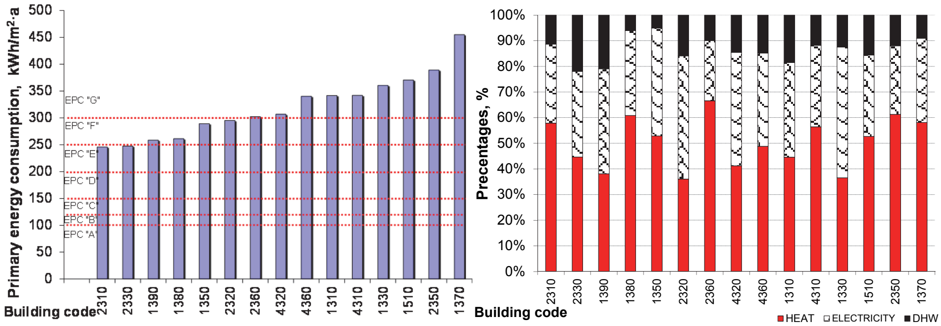


Figure 4.10 Primary energy consumption of the buildings and distribution between heating, electricity and domestic hot water.

4.2.2 Energy balance and energy savings of different renovation measures

To show the influence of single renovation measures, the delivered energy (DE) and primary energy consumption (PE) simulations were done using renovation measures one at a time and comparing the result to the reference case (BC). District heating (DH), a gas condensing boiler (GB), a pellet boiler (WPB) and an air to water heat pump (AWHP) as new heat sources with hydronic radiators were compared with existing wood heating stoves (see Table 4.2). Additional thermal insulation for the facade (20…270 mm), for the attic floor (100…400 mm), for the basement floor (100…200 mm) and retrofit of windows (U=1.8…0.8 W/(m^2·K)) as insulation measures were compared.

Table 4.2 Influence of single energy renovation measures

Energy renovation measures	DE		PE	
	Average / range, kW/(m^2·a)	Decrease from base case, %	Average / range, kW/(m^2·a)	Decrease from base case, %
Base case				
Original structures, stove heating + exhaust ventilation + electricity for DHW	449 / 369…517	0	416/ 353…463	0
Improvement of building envelope				
AF200. Attic floor /roof: +200mm insulation: U 0.17 W/(m^2·K)	414 / 332…479	-8	390/ 325…435	-6
AF400. Attic floor /roof: +400mm insulation: U 0.11 W/(m^2·K)	408 / 326…473	-9	385/ 321…430	-7
BF100. Basement ceiling: +100mm insulation: U 0.21 W/(m^2·K)	434 / 363…498	-3	404/ 349…448	-3
EW20. External wall +20mm insulation: U 0.51 W/(m^2·K)	428 / 351…489	-5	400/ 339…442	-4
EW70. External wall +70mm insulation: U 0.34 W/(m^2·K)	401 / 334…456	-11	380/ 327…417	-9
EW120. External wall +120mm insulation: U 0.24 W/(m^2·K)	386 / 325…441	-14	369/ 320…406	-11
EW170. External wall +170mm insulation: U 0.19 W/(m^2·K)	377 / 321…429	-16	362/ 317…397	-13
EW220. External wall +220mm insulation: U 0.13 W/(m^2·K)	372 / 319…423	-17	363/ 319…398	-14
W1.8. Window renovation: U 1.8 W/(m^2·K)	421 / 345…481	-6	395/ 335…436	-5
W1.4. Window replacement: new U 1.4 W/(m^2·K)	416 / 340…474	-7	391/ 331…431	-6
W1.1. Window replacement: new U 1.1 W/(m^2·K)	404 / 331…462	-10	382/ 324…422	-8
W0.8. Window replacement: new U 0.8 W/(m^2·K)	394 / 321…451	-12	374/ 317…414	-10
Improvement of HVAC systems				
HR60. Balanced ventilation with heat recovery 60%	394 / 314…454	-12	384/ 320…428	-8
HR80. Balanced ventilation with heat recovery 80%	365 / 281…438	-19	362/ 295…415	-13
DH. District heating for room heating, ventilation and DHW	240 / 202…270	-46	272/ 234…299	-35
GB. Gas boiler heating for room heating, ventilation and DHW	251 / 211…282	-44	283/ 243…312	-32
WPB. Pellet boiler for room heating, ventilation and DHW	277 / 232…312	-38	248/ 214…271	-40
AWHP. Air to water heat pump for room heating, ventilation and DHW	132 / 114…145	-70	264/ 228…290	-36

Figure 4.11 compares different single energy renovation measures taking into account the change of the primary energy use (horizontal axis) and the difference of the global cost of the reference case and the renovated case (vertical axis). The dots in Figure 4.11 show the average of a single renovation measure of the four buildings. The solid lines in Figure 4.11 show dependency of the global cost difference on the PE savings in the case of a single renovation measure.

From the single insulation measures, adding insulation to the external wall is most effective to gain energy savings; in terms of cost, adding insulation to the attic floor is most effective. A clear turning point can be seen in the cost optimal curve of different renovation measures. Some of the renovation measures can be considered expensive in terms of the amount of energy saved by implementing the renovation measure. From the improvement of the HVAC systems, the change from an existing heating system to pellet boiler heating gives the largest gain in PE savings and is also the most cost effective.

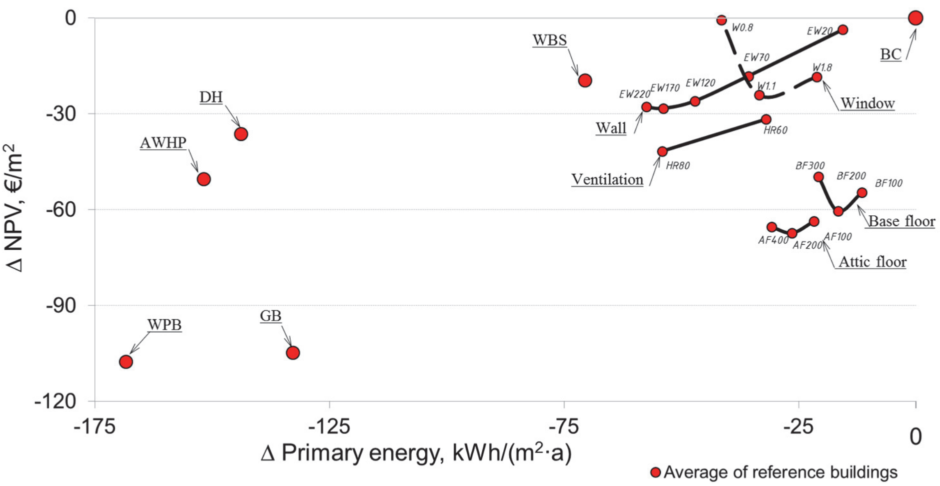


Figure 4.11 The economic impact of different renovation measures.

In the second step, the renovation packages were combined using single renovation measures (Table 4.2). The results are presented in three different groups (Table 4.3): packages according to current renovation practice (BAU), packages that alter the architectural appearance the least to save heritage buildings (HER), and packages with the best economic effect (ECO). These three can be seen as representative of the different attitudes of different building owners. The packages are presented to attain different energy savings from -20% as a minimum primary energy saving to -55% as PE requirement for existing buildings that are subject to major renovation; and "max" as the lowest PE consumption of simulation cases. In the BAU case, the mechanical exhaust ventilation system with the air compensation through the fresh air valves is considered in the indoor climate category III (EN15251 2007): 0.35 l/(s·m²). In the cases of HER and ECO, the new mechanical exhaust-supply ventilation system with heat recovery is considered together with the improvement of air flows to the indoor climate category level II (EN15251 2007), from 0.35 l/(s·m²) to 0.42 l/(sm²).

Table 4.3 Primary energy consumption, savings, and economic assessment of the renovation packages

Renovation packages	Renovation measures													Assessment values			
	Attic floor		Base floor	Window			External wall				Service systems			PE		ΔNPV	
	AF 200	AF 400	BF100	W1.8	W1.1	W0.8	EW20	EW70	EW120	EW170	WBS new	HR80%	New heat source	kWh/(m²·a)	% of savings	+3% energy price	+5% energy price
BAU		x	x	x				x						318	23	-3	-21
-20% HER											x	x		308	26	-20	-39
ECO	x		x									x		323	22	-24	-40
BAU		x	x		x			x						262	37	22	-5
-35% HER		x	x									x		270	35	12	-12
ECO													x	267	36	-75	-98
BAU		x	x		x					x			x	193	56	40	5
-55% HER		x	x			x	x					x	x	174	58	1	-39
ECO		x	x		x			x				x	x	174	58	22	-20
MAX		x	x			x				x		x	x	162	61	46	2

The energy saved long-term as a result of retrofit lowers the annual energy costs. The costs are adjusted to current Euro values and are used to compare the renovation packages. If the latter is equal to or smaller than the reference case, the renovation measure can be considered economically viable. The results for different building types vary to a large degree. If the results are divided into groups according to the heat source, then the average curves can be drawn to see the differences between the renovation packages. The curves in Figure 4.12 indicate clearly how the heat source influences the possible energy savings and future annual energy costs. The starting point of the curve shows the lowest energy savings as per different heat sources. The limit of 180 kWh/(m^2·a) for the buildings under major renovations can be achieved only if the wood-burning stove heating is replaced for a new heating system. Comparing the ΔNPV, only the pellet and the gas boiler are on the negative side and therefore can be considered economical.

An economically optimal solution is assumed to be achieved if the ΔNPV is the lowest. The lowest ΔNPV for different packages with different heat sources is presented in Figure 4.12. Small grey dots show the distribution of all the results of the simulated cases of the different reference buildings. The coloured dots show the average of different reference buildings with the same heat source and renovation measures. The curve for the minimum ΔNPV is combined with the different renovation packages with different heat sources. The curves stay on the negative side for a wide range, indicating that renovation packages can be economically viable if a new heating system is considered. The minimum ΔNPV curve stays below the zero line, offering a wide range of opportunities to choose the renovation packages depending on the desired PE with different heat sources and insulation measures. In the case of the historic buildings with the facades that are worth preserving and a desire to keep the characteristics, the renovation measures affecting the appearance the least have to be considered first.

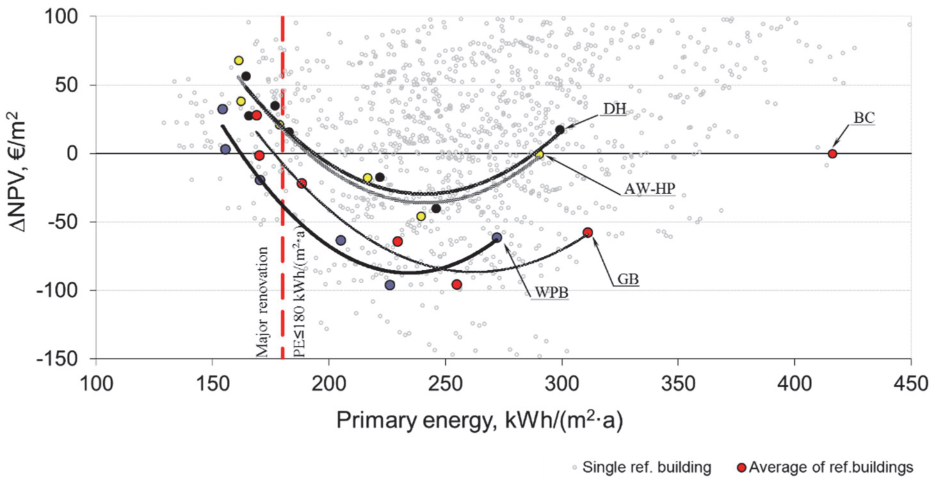


Figure 4.12 Minimum ΔNPV for different renovation packages with different heat sources.

Figure 4.13 shows the differences between the renovation packages when the architectural appearance of the building is considered in comparison with the current renovation practice and the highest economical effect. In the case of BAU, stove heating is considered, and in the cases of HER and ECO, the curves are presented as an average of the different heat sources.

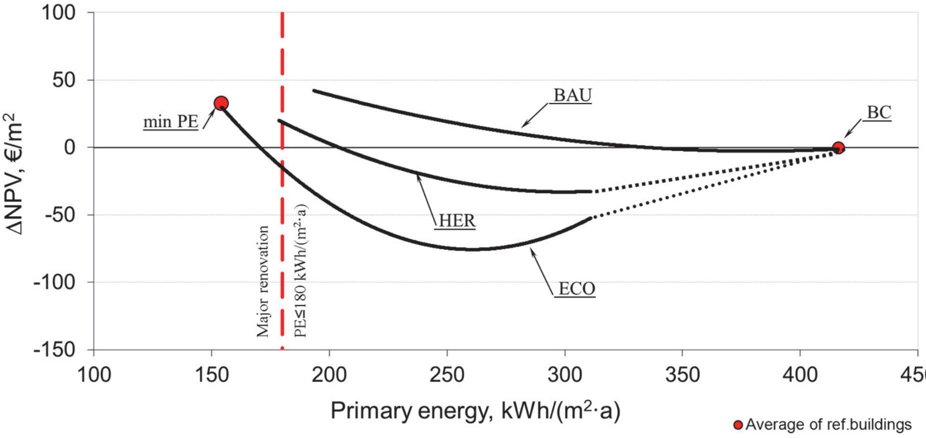


Figure 4.13 Comparison of renovation packages considering different attitudes and requirements.

4.3 Hygrothermal performance of the log wall with interior thermal insulation

4.3.1 Field measurement results

Hourly temperature and RH data were measured and collected nearly throughout a one-year period: 12.12.2009…6.10.2010. Outdoor temperature during the measurement period varied between -21.5 °C…+33.6 °C and RH between 22%...100%. During winter the average temperature was -7.4 °C (min -21.5 °C, max +4.2 °C) and RH 89% (min 62%, max 100%). The annual indoor temperature in the bedroom varied between +13.5 °C…+27.5 °C and RH between 43%...83%. During winter months, the average indoor temperature was +17.4 °C (min +13.5 °C, max +24.5 °C) and RH 64% (min 43%, max 74%). Coincidentally, measurements were conducted in apartments with the highest indoor humidity loads, when we compare indoor humidity loads in all studied apartments.

Figure 4.14 left shows the dependence of the indoor temperature on the outdoor temperature. Each dot represents the measured value corresponding to the outdoor temperature. The indoor temperature depends quite linearly on the outdoor temperature. This indicates that problems exist with sufficient heating power of the heating system. The average indoor temperature stays below the lowest category of thermal comfort 50% of the time during winter due to low indoor temperatures.

Dependence of the moisture excess on the outdoor temperature is shown in Figure 4.14 right. From this data, the 90% critical level (Sanders 1996) was calculated (black dotted line). During cold periods, the weekly average internal moisture excess was between +7 g/m^3. Based on earlier studies in Estonian dwellings (Kalamees 2006), the studied apartment may be classified as a dwelling with a very high humidity load. The humidity load was high due to low ventilation (natural ventilation), higher occupancy (23 m^2/pers.), and possible drying out of structural moisture (some living rooms located in the basement connected with living rooms on the 1st floor).

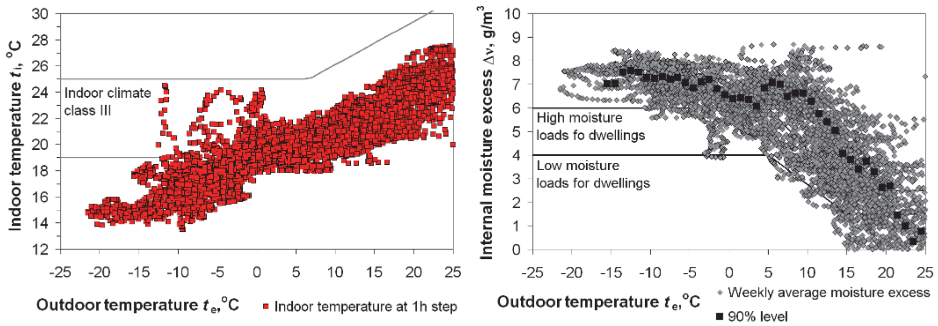


Figure 4.14 Dependence of the indoor temperature and moisture excess on outdoor temperature.

Due to low temperature and high humidity loads, indoor RH was high during cold period. The indoor RH stays above the rule of thumb criteria for indoor RH during winter in Estonia (RH 25…45%) most of the time (Figure 4.15).

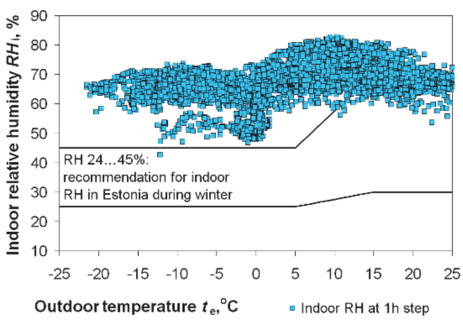


Figure 4.15 Dependence of the indoor RH on the outdoor temperature. Reference point to assess the hygrothermal performance of the internally insulated wall was between the original log and the internal insulation, see Figure 3.11 left.

Indoor and outdoor temperatures as well as temperatures inside the wall between the insulation material and the log layer are shown in Figure 4.16 (daily running-average). During the measurement period, the lowest temperature on the internal surface of the log was observed in the case of mineral wool insulation. This corresponds also well to the lowest thermal conductivity of that insulation material.

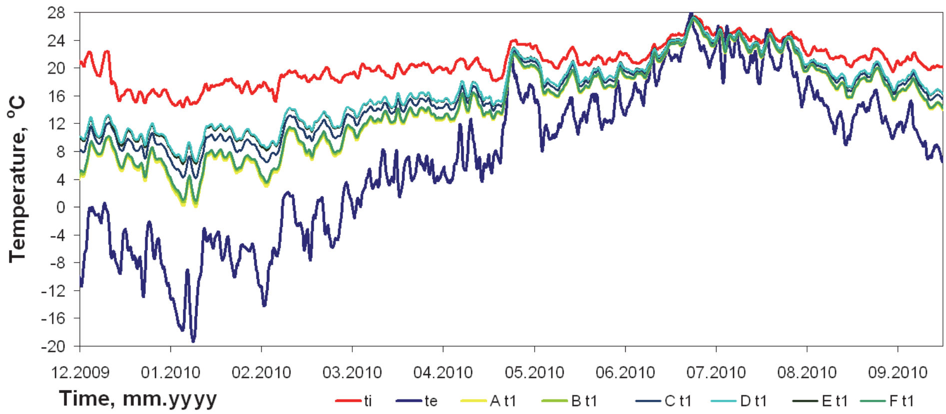


Figure 4.16 Measured temperatures inside the wall between the insulation materials.

RH was high throughout the winter-spring period (Figure 4.17). RH was close to the upper measurement limit, indicating possible moisture condensation to the inner surface of the log. Also, the calculated steady-state vapour distribution in the wall indicated possible moisture condensation in the wall between the insulation material and the log layer. The RH was highest in test walls with mineral wool insulation. On the other hand, test walls with mineral wool insulation dried more quickly than the wall with cellulose or reed insulation mat during summer period.

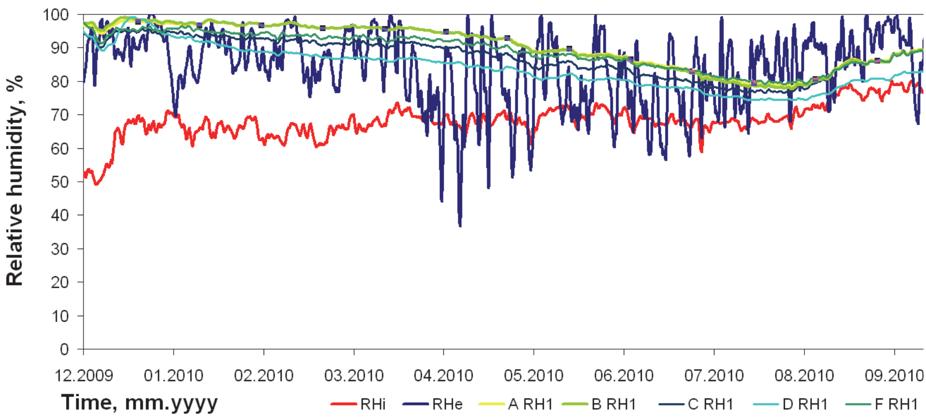


Figure 4.17 Measured RH inside the wall between the insulation materials.

Water vapour pressure in the indoor and outdoor air as well as inside the wall between the insulation layer and the log layer are presented in Figure 4.18. During the spring-summer period the air vapour pressure inside the wall was higher than the air vapour pressure in the bedroom, indicating the drying of the wall to the indoor air. Water vapour pressure was higher in the test walls with hygroscopic thermal insulation.

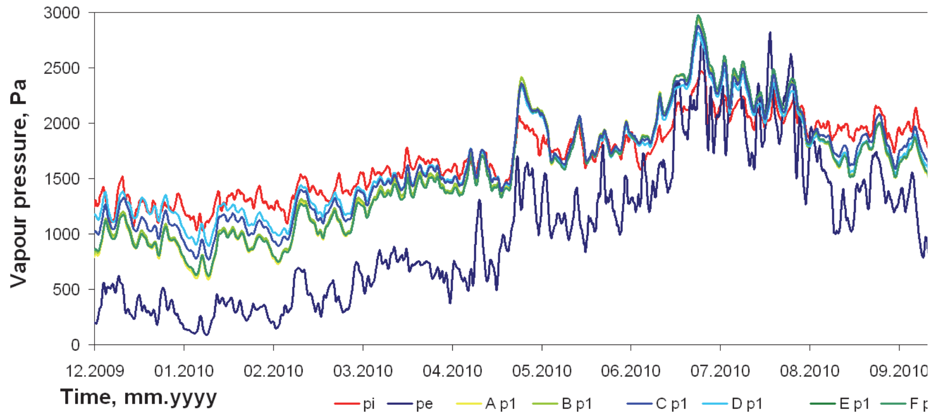


Figure 4.18 Measured water vapour pressure inside the wall between the insulation materials.

The RH on the inner surface of the log wall stayed at the high level during the whole measurement period. Based on the mould growth model (Hukka & Viitanen 1999) in all the cases, the temperature and RH level inside the wall exceeded the temperature and relative humidity conditions favouring initiation of mould growth on wooden materials, see Figure 4.19.

In the case of the mineral wool insulation, temperature and RH conditions are favourable for mould growth more than 88% of the time. With cellulose insulation, the risk for mould growth is higher in walls without air- and vapour barrier (84 % of measured time length) than with air- and vapour barrier (75 % of measured time length). With the reed insulation mat, more than 93% of the time is favourable for mould growth. According to the mould growth assessment, there should be a high risk for mould growth.

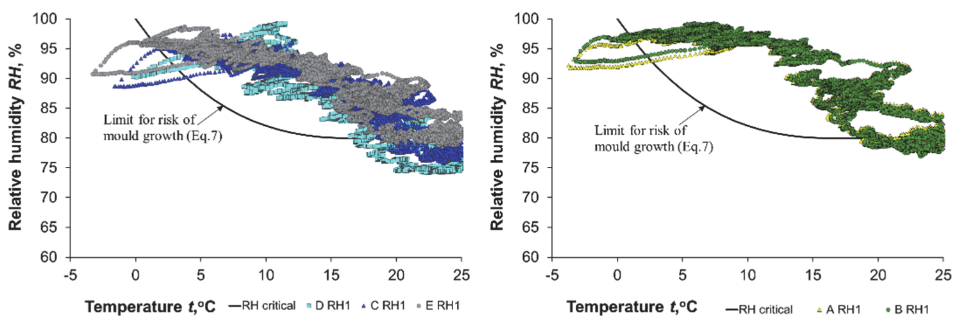


Figure 4.19 Temperature and RH conditions are favourable for mould growth for “green” insulations (left) and for mineral wool (right).

In spring 2010, exterior walls were opened in all rooms in several places where interior insulation was installed to measure the moisture content of logs and to take samples for determining possible microbial growth. Moisture measurements showed high moisture content of logs (Figure 4.20 left): 19…29%. Mould growth was also determined visually (Figure 4.20 right).

Figure 4.20 High moisture content of the log (left) and visual mould growth (right) in the case of log wall insulated from the interior side.

4.3.2 Validation of the HAM simulation model

Two potentials for moisture flow are introduced in the WUFI. The liquid transport flux depends on the relative humidity and the water vapour diffusion flux depends on the vapour pressure in a porous hygroscopic building material.

In the studied walls, the hygrothermal properties of wood play an important role, because the log layer is a geometrically dominating material and has the highest moisture storage properties. In different cases, the moisture flow through the log layer was described by the vapour diffusion resistance factor and capillary flow according to the cases shown in Figure 3.13. The results in the case of mineral wool without any convective air flow are shown in Figure 4.21.

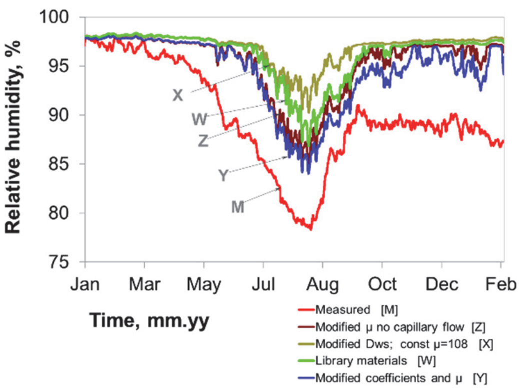


Figure 4.21 Calculated RH inside the reference wall “A” between the insulation (mineral wool) and the log layer.

In all cases the calculated relative humidity values were higher than the measured values. There was no good correlation between the measured and calculated results. In all cases the slope of drying and wetting follows the measured value line but drying starts later and lasts for a shorter time. Therefore the RH level stays higher than the measured RH level.

The RH values after the wetting process are on the same level in the case of the library materials and modified liquid transfer coefficients with a constant vapour diffusion resistance factor equal to dry material. In contrast, there is a difference between the changes in the RH levels before the drying. The reason for that may be the speed of moisture transport. The closest results to the measured results are with the moisture dependent vapour diffusion resistance factor and with increased liquid transfer coefficients affecting in the hygroscopic range. At changes in the liquid transport coefficients, the proportion of the capillary flow was increased on the lower levels of RH.

The slope of drying and wetting follows the measured value line and drying starts later and lasts for a longer time than in case without a capillary flow. Therefore, the simulations with changed liquid transport coefficients gave better results.

Air tightness measurements showed the air leakage rate of the building envelope q_{50}= 7.4 $m^3/(h \cdot m^2)$. In addition, the poor air tightness of the existing log layer favours the convective flow through gaps, cracks and holes inside the wall. Therefore in real life the air leakages exist through the log layer in the wall. Airflow inside the insulation layer influences moisture conditions of an internally insulated log wall in a cold climate (Ojanen 2007).

The air flow was added in the simulation model, so the air inside the wall is mixed with the outdoor air. The air change source described in the simulation model is shown in Figure 3.12. The added air flow lowered the RH level inside the wall between the insulation and the log layer in all cases. The simulation results with the convection inside the wall are presented in Figure 4.22.

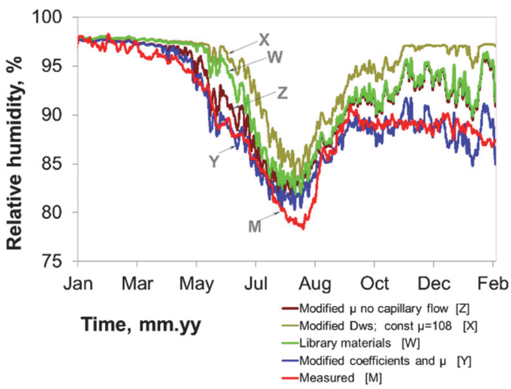


Figure 4.22 Calculated RH inside the wall A between the insulation (mineral wool) and the log layer with the air change rates.

The simulation results show good correlation between the measured values and the calculated values when the liquid transport coefficients start to affect in the hygroscopic range and the air flow is considered. During spring the drying and during autumn the wetting are well in line with the measured results.

The comparison of calculated temperature and measured temperature showed very good agreement for a wall with mineral insulation (reference wall “A”). Temperature and relative humidity levels in the wall between the log and the mineral wool are presented in Figure 4.23. In the case of the reed insulation mat and the cellulose wadding, the calculated temperatures showed good agreement with the measured temperatures, but as compared to mineral insulation, in the case of the RH larger discrepancies occurred during the drying and the wetting period.

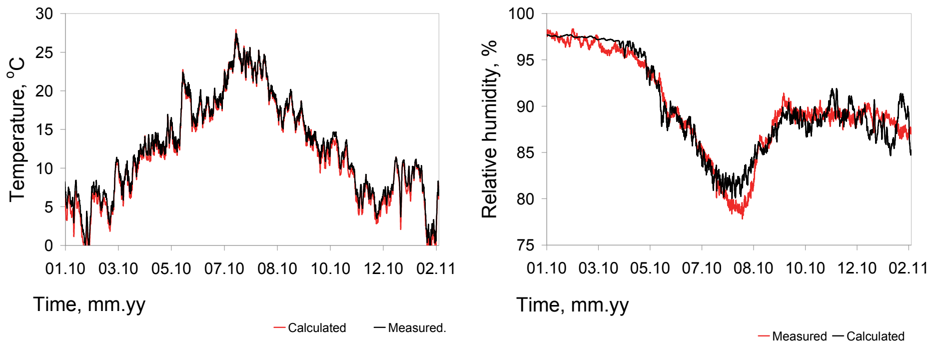


Figure 4.23 Calculated temperature and RH inside wall A between the insulation (mineral wool) and the log layer.

4.3.3 Moisture safety and reliability of the interior thermal insulation on the log wall in Estonian climate

The validated WUFI model was used to simulate the temperature and RH conditions in a retrofitted wall with interior insulation. Using the simulation results, the *M index* was calculated to assess the performance of the interior insulation. The *M indexes* calculated in the first step for 100 randomly generated cases are presented in Figure 4.24. As a result of success (*M index* < 1) and failures (*M index* ≥ 1), it was found that the unwanted outcome occurred in 17 cases and 83 of the cases were safe. In 17 cases out of 100, a statistical probability of interior insulation failure is 13%. In the 30-year calculation period, the unwanted outcome occurred in 26 cases and 74 of the cases were safe, a statistical probability failure is 26%.

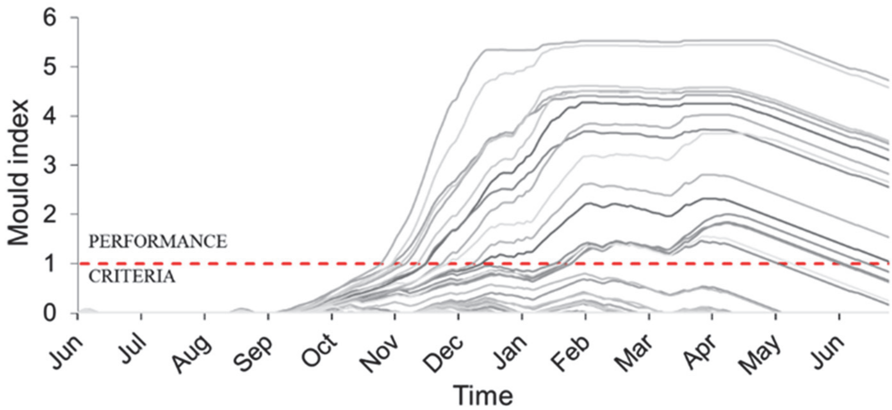


Figure 4.24 Calculated mould index between the log and the interior insulation layer of randomly generated 100 cases for a one-year period.

Logistic regression coefficients are presented in Table 4.4. Indoor temperature, moisture excess, insulation layer thickness, thermal conductivity of the insulation material, log layer thickness and existence of the vapour barrier were selected as changing variables, which are all statistically significant.

The coefficients returned from a logistic regression model express how the probability of the unwanted event to occur changes with a one-unit change in the independent variable. The sign of the coefficient indicates the direction of its relationship: ’+’ means a positive relationship between and the likelihood of a success, and ‘-‘ means a negative relationship. In the studied case, the variable with the positive coefficient indicates that increasing the value of the variable raises the probability for the unwanted outcome (*M index*>1) to occur and the variable with the negative coefficient indicates that decreasing the value of the variable increases the probability of the event (*M index*>1) to occur.

Table 4.4 Probabilistic parameters and regression coefficients

Input variable	Design value and distribution*	*R* outcome		
		Coefficients	Standard error	p-value
Intercept		-2.578	0.458	$1.87 \cdot 10^{-8}$
Thickness of insulation, mm	50±30 (*U**)	6.373	0.876	$3.56 \cdot 10^{-13}$
Thermal conductivity λ,(W/(m·K)	0.038±0.018 (*U**)	-6.709	0.918	$2.78 \cdot 10^{-13}$
Indoor temperature $t_{i,}$ °C	22.0±2.15 (*N**)	-2.429	0.430	$1.59 \cdot 10^{-8}$
Moisture excess Δν, g/m^3	2.51±1.07 (*N**)	4.051	0.603	$1.80 \cdot 10^{-11}$
Vapour barrier	1 [yes]/0 [no] (*D**)	-4.757	0.779	$1.0 \cdot 10^{-9}$
Thickness of log, mm	145±30 (*U**)	-2.010	0.391	$2.75 \cdot 10^{-7}$

*explanation of distributions: *U* - uniform distribution between min and max value; *D* – discrete uniform distribution with option *a* and *b*; *N* – normal distribution with mean value ±standard deviation;

Intercept gives the odds for the unwanted outcome to occur in the base case. The probability for *M index* >1 in the base case is 0%. If the vapour barrier is not installed or is broken, then the probability for a solution to fail (*M index* >1) is 7 %, in the 0.95 confidence intervals 3% to 19%.

In the sensitivity analyses, the existence of the vapour barrier is the most influential, because the wall is composed with exterior boarding that prevents the rain load and only moisture load is from indoors. In addition to the vapour barrier, the properties of the insulation material layer (thickness and thermal conductivity) are of critical significance. From the boundary conditions, the value of the moisture excess has a higher effect than that of the indoor temperature. The effect of the single variable with and without vapour barrier is presented in Figure 4.25.

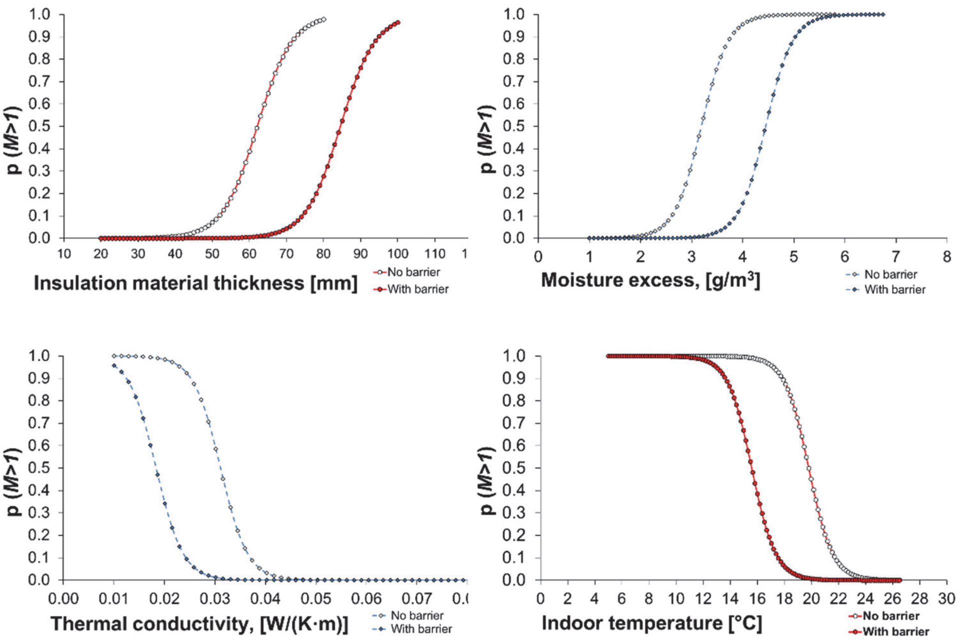


Figure 4.25 The change in probability of mould index (*M index*>1) for different variables with and without vapour barrier.

Figure 4.26 presents changes in the probability of *M index*>1 at different insulation material layer thicknesses with and without vapour barrier in combination with average thermal conductivity, average log layer thickness and different indoor temperature and moisture excess. For indoor temperature (T_i) and moisture excess (Δv), the combinations of avg ± st.dev values are considered (T_{iavg}; $T_i+\sigma_T$; $T_i-\sigma_T$; Δv_{avg}; $\Delta v+\sigma_{\Delta v}$; $\Delta v-\sigma_{\Delta v}$).

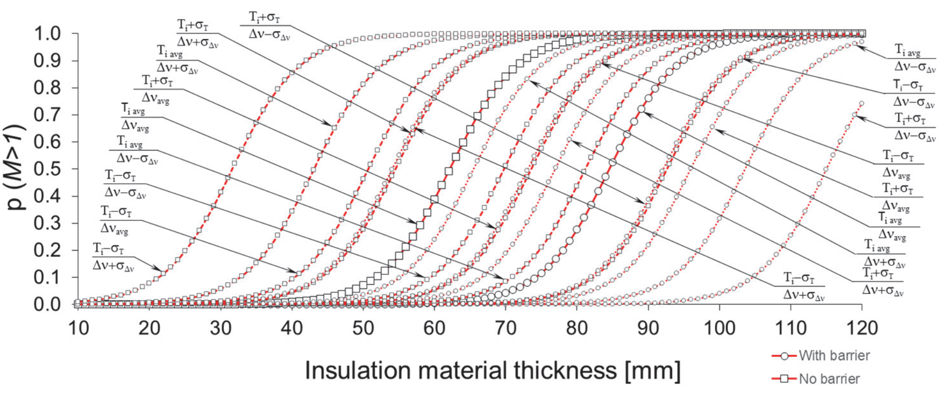


Figure 4.26 Change in the probability of mould index (*M index>1*) in the combination of different input variables with and without vapour barrier.

Depending on the variables, the probability for a solution to function without failure is between 0 and 100%. The question is where the line can be drawn, whether the unwanted outcome occurs or not. Using the regression coefficients, the probability of the unwanted outcome (*M index*>1) to occur can be calculated by Eq. 8. To find the relation between the regressions analysis and the *M index*, the combinations of input variables generated for the first step WUFI simulations were used. The probabilities for the 100 simulation cases were calculated and compared with *M index* calculation results from the first step. The correlation between the calculated *M indexe*s and the probabilities of a solution to function without failure of randomly generated 100 calculation cases are presented in Figure 4.27.

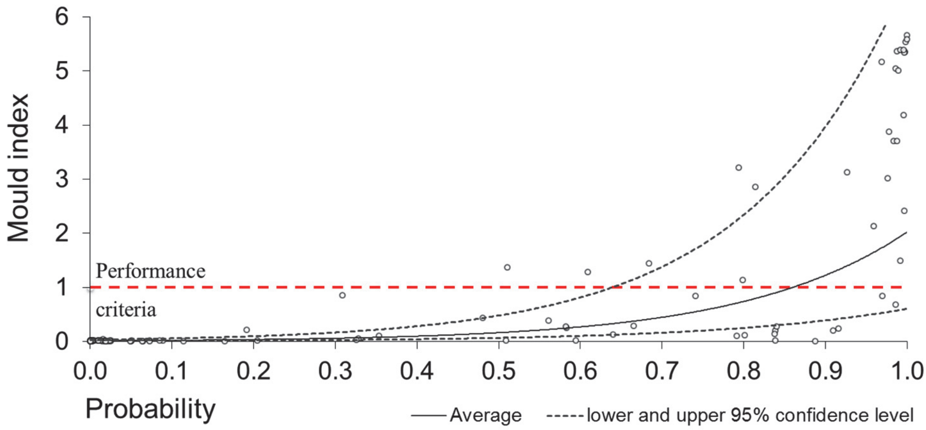


Figure 4.27 Correlation between the mould index and the probability of a solution to function without failure.

To assess the reliability, the boundary between safe and failure can be drawn in the intersection of the assessment criteria line and the probability line. The average probability for a solution to function without failure is 86% in the 0.95 confidence intervals 64% to 100%.

Based on the stochastic calculations, at the safety margin set on the lower 0.95 confidence level, statistical probability to fail is 37% for the 50 mm thick interior insulation on the 145 mm thick log wall in typical indoor and outdoor climate conditions in Estonia.

4.4 Method to take into account milieu values of districts on a building's level during energy renovation

There were three most critical junctions on the façade of the wooden apartment building in milieu valuable districts relevant also in the case of a studied building:

- the basement wall and the external wall;
- the window and the external wall;
- the external wall and the eave.

Typically, in wooden apartment buildings, the basement wall protrudes the external wall, the windows are located in the same plane with the external wall cladding without any protrude or step back, and the eaves have decorated rafters. The inventory of wooden apartment buildings composed in cooperation with professional conservators from Estonian Art Academy concluded the following:

- protrude of the basement wall is 3 – 10 cm; it is still acceptable in terms of milieu values if the basement wall is in the same plane with the external wall because of the dripping board between the basement wall and the external wall;
- max 7 cm step back in the case of window fem boarding is still acceptable in terms of milieu values;
- the eaves have decorated rafters that have to step out and cannot be hidden in the external wall, it is still acceptable in terms of milieu values if the rafters step out for 5 – 10 cm.

Based on the measurements and expert assessments, an evaluation matrix was composed to grade the influence of different retrofit measures on the characteristics of the building (Table 4.5).

Different renovation packages were considered to find out the improvement of the energy performance and the influence on the characteristics of the building. Since the architectural appearance of a building is regarded valuable, the packages consisting of insulation measures were assessed. The average grade for the renovation packages was calculated based on the evaluation matrix (Table 4.5). The average grade are calculated taking into account all the single renovation measures in the specific renovation package and their influence on the different junctions of the building compared to starting conditions. The average grade shows the alteration of the milieu values of the building.

Table 4.5 Evaluation matrix for energy renovation measures

Other structures	External wall							
Starting conditions of the building: • 1 - original facade • –1 - typical condition • –3 - old façade not original Grades to retrofit measures: • 0 - no influence • –1 - undetectable influence • –3 - tolerable influence • –5 - strong negative influence • –7 - intolerable influence Assumptions: • replica of original solution is acceptable • construction works follows the best practice	Original facade	Typical condition	Old facade (not original)	Replica of original facade, no insulation	EW20. External wall +20mm insulation: U 0.51 W/(m²·K)	EW70. External wall +70mm insulation: U 0.34 W/(m²·K)	EW120. External wall +120mm insulation: U 0.24 W/(m²·K)	EW170. External wall +170mm insulation: U 0.19 W/(m²·K)
AF0. Original attic floor	1	-1	-3	1	-1	-3	-5	-7
AF200. Attic floor /roof: +200mm insulation: *U 0.17 W/(m²·K)**	1	-1	-3	1	-1	-3 / -1	-5 / -1	-7 / -1
AF400. Attic floor /roof: +400mm insulation: *U 0.11 W/(m²·K)**	1	-1	-3	1	-1	-3 / -1	-5 / -1	-7 / -1
BF0. Original basement ceiling	1	0	0	0	0	0	0	0
BF100. Basement ceiling:100mm insulation: *U 0.21 W/(m²·K)*	1	0	0	0	0	0	0	0
W2.8. Original window in original place: *U 2.8 W/(m²·K)*	1	-1	-3	1	-1	-3	-5	-7
W1.8. Window renovation: in original place *U 1.8 W/(m²·K)*	1	-1	-3	1	-1	-3	-5	-7
W1.4. Window replacement: new window *U 1.4 W/(m²·K)***	-1	-1	-3	0	-1	-3 / -1	-5 / -1	-7 / -1
W1.1. Window replacement: new window *U 1.1 W/(m²·K)***	-1	-3	-3	0	-2	-3 / -2	-5 / -2	-7 / -2
BW0. Basement wall, no insulation (original)	1	-1	-1	-1	-1	-3	-5	-7
BW70. Basement wall +70mm insulation: *U 0.34 W/(m²·K)*	-3	-3	-3	-3	-3	-1	-3	-5
BW120. Basement wall +120mm insulation: *U 0.24 W/(m²·K)*	-5	-5	-5	-5	-5	-3	-1	-3
BW170. Basement wall +170mm insulation: *U 0.24 W/(m²·K)*	-7	-7	-7	-7	-7	-5	-3	-1

*eaves left in original place / eaves and rafters lengthened; **new window installed in place of original window / new in new place (Fig.1, d)

Different renovation packages were considered to find out the improvement of the energy performance and the influence on the characteristics of the building. The results of the improvement in the energy performance value and the influence on the milieu value are presented in Figure 4.29. The starting point for the energy performance value is 558 kWh/(m^2·a), the influence is presented in two different cases, first for a building in typical conditions that needs to be repaired in the near future (Figure 4.29), and second, for a building in a good condition, where renovation is motivated to improve the energy performances and thermal comfort (Figure 4.29).

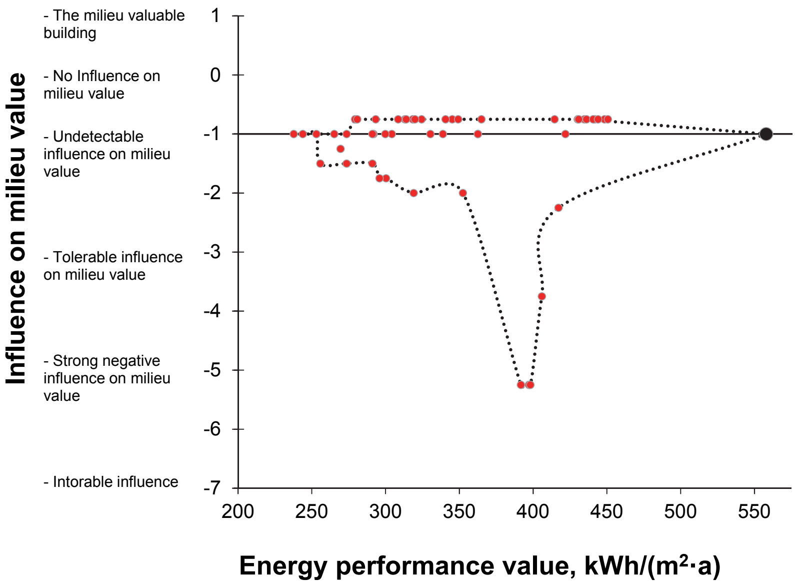


Figure 4.28 Influence of energy performance improvements on the architectural appearance of the milieu valuable wooden apartment building.

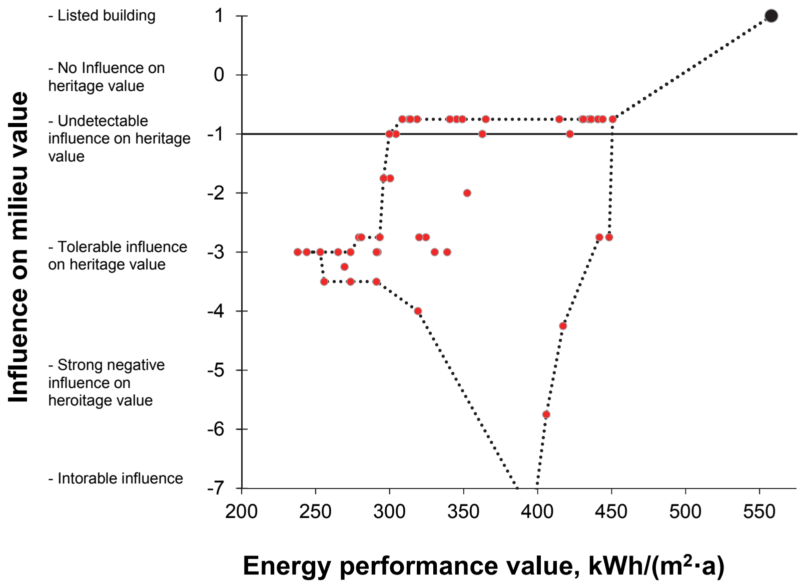


Figure 4.29 Influence of energy performance improvements on the architectural appearance of the wooden apartment building listed as monument.

The starting condition of the building has a strong influence on the overall grade of the renovation measures. Improvement of energy performance influences the milieu values. If only few renovation measures are taken, negative influence on the milieu value is the largest. The reason is that the external thermal insulation is considered without any changes in other constructions or junctions connected to the external wall. In complete energy renovation with larger savings, different building envelope parts need to be renovated and it is possible to do all connections such that the value of the district is not demolished. But in both cases, the whole building renovation is preferred when the energy savings are larger and the overall influence on the milieu value is smaller. The reason is that if the whole building is renovated, then all the different parts of the building are also taken into account and it is easier to solve the junctions of the façade elements without degrading the architectural appearance of the building.

5 DISCUSSION

5.1 Indoor climate

International standards like ISO7730 and ASHRAE 55 have derived substantially from the studies of thermal comfort, to guide the built environment professions to design and maintain comfortable indoor thermal environments (deDear 2004) but in reality the conditions may differ considerably.

The results show that while the average indoor temperature during the winter period was +21.0 ºC, large variations occurred in indoor temperatures. Due to large heat losses and insufficient heating capacities, the measured indoor temperature was lower during the colder period. At lower outdoor temperatures, scattering in the measured results showed almost two times larger deviation than at the warmer outdoor temperatures. Large variations in the indoor temperature can be explained by the characteristics of a particular building, such as low thermal transmittance of building constructions, large air leakages and insufficient power of heating systems as well as by the behaviour of the occupants (Becker & Paciuk 2009).

Typical conditions with typical variation should be used for stochastic analysis. The average value of weekly average moisture excess values from different rooms over the cold period in Estonian detached houses was +1.5 g/m^3 and over the remaining time +0.2 g/m^3 and in Finnish detached houses +1.8 g/m^3 and during the remaining time +0.5 g/m^3. According to Kalamees (2006), during the cold period, the average value of the weekly average moisture excess was +3.2 g/m3 in Estonian apartments. Geving and Holme (2012) measured average internal moisture excess in bedrooms and living rooms 1.8 g/m^3 and 2.1 g/m^3, respectively. In the current study the, average occupant density was 26 m^2 per person (0.04 pers/m^2). The average moisture excess level in an historic wooden apartment building is higher (+3.3 g/m^3) than average measured by Kalamees et al. (2006), Kalamees (2006), and Geving & Holme (2012), which correlates with higher living density and lower ventilation air change rate. The design curve proposed in this study is lower than previous studies (Kalamees (2006), Vinha (2007), Geving & Holme (2012)) have shown. The reason is that the design curve presented in this work is for stochastic analysis while that in previous studies was meant for deterministic analysis.

Metabolic CO_2 can be used as an indoor air quality indicator. Indoor CO_2 concentrations above 1000 ppm are generally regarded as an indicator of inadequate ventilation. In Nordic residential buildings, ventilation rates below half an air change per hour are considered too low, which may lead to high concentrations of pollutants that may cause health problems (Wargocki et al. 2002, Sundell et al. 2011). The air change rate is low and it is necessary to improve ventilation of the historic wooden apartment buildings to ensure better IEQ. In addition, the ventilation rates influence the indoor humidity. Ventilation usually reduces indoor moisture levels. Older buildings and the use of natural ventilation are associated with increased frequency of dampness indicators as well as with increased frequency of complaints on bad indoor air quality (Hägerhed et al. 2002). In the studied buildings, the frequency of overall appearance of spores in the indoor air is distributed unevenly. But the largest numbers of spores found in the indoor air of the wooden apartment buildings were also the spores with the highest health risk (Singh 2000). Depending on the inhabitants' response, the number of spores in the indoor air need not be very high to cause health problems. The quantity of spores in the indoor air of more than 50% of the studied wooden apartment buildings was lower than 150 cfu/m^3 and was smaller than the number of different fungal species in the indoor air in the brick and concrete element apartment buildings (Kalamees et al. 2011). The results show that ventilation in wooden apartment buildings is inadequate since the presented air-change values include also air change between other rooms when the communicating door is open. Nonetheless, taking into account the high living density and poor thermal transmittance of the buildings, air samples with the quantity of spores lower than 150 cfu/m^3 were found in more than half the buildings. The result seems good and it is in correlation with the number of air samples with no spores. The main reason is that there are fewer critical thermal bridges in wooden apartment buildings than, for example, in brick and prefabricated reinforced concrete large-panel element apartment buildings (concrete element) (Ilomets et al. 2014).

Overall, in the historic wooden buildings, occupants' complaints about the indoor climate conditions are not in a majority. In our study, most of the complaints concern unstable temperature and low temperature of the floor during the winter period rather than the air quality or noise problems. The reason is that the building occupants rank thermal comfort of greater importance than good air quality and acoustic comfort (Frontczak & Wargocki 2011). Another reason may be that human adaptation is more active in naturally ventilated buildings and that the zone of equal thermal sensation for naturally ventilated building occupants is generally broader than for that in heated and ventilated and air conditioned buildings. In naturally ventilated buildings, the thresholds are broad due to the occupant-adaptive behaviour in the presence of outdoor climate (Zhang et al. 2011). In most of the studied buildings, inhabitants have available control over the environment and this has been seen as the indoor environment improvement factor (Frontczak & Wargocki 2011). Because of the peculiarities of historic buildings, their occupants tend to tolerate deficiencies characteristic of historic wooden apartments to a greater extent than those typical of more recent types.

5.2 Energy performance

The average measured primary energy consumption in historic wooden apartment buildings was 331 kWh/(m^2·a) (st.dev. 72 kWh/(m^2·a)) , that is 25% higher than PE usage in typical brick apartment buildings in Estonia (Kuusk et al. 2014). The main reasons for higher energy usage are larger heat losses through the building envelope (thermal transmittance, air leakages) and ineffective heat source for heating of rooms and DHW.

The calculated EPV of all the studied buildings was higher than the limit set for existing buildings subject to major renovation presented in (Ordinance No. 68 2012). In most of the buildings, the average electricity and water use was below the level used to calculate the PE consumption in standardised use. If the energy used for hot water heating is subtracted, then 75% of the buildings will consume less than 30 kWh/(m^2·a), which was used in our energy performance calculations. The average domestic hot water consumption below 520 l/(m^2·a) was used in our energy performance calculations. Overall 76% of the buildings studied used less than 520 l/(m^2·a). The PE and the distribution between different systems reveal a great potential for heating energy savings.

The key to energy savings is in the reduction of the heat losses through the building envelope. Heat losses can be reduced by adding insulation to the external walls, floors or roof, replacing the glazing or changing the windows. In addition, in historic wooden apartment buildings, air tightness is an important aspect of energy efficiency. Therefore, improving the building envelope also has a positive effect at air leakages and thermal bridges. According to Homb (2012), instead of replacing existing windows, they can be made more energy efficient. Though adding insulation to the external wall is most labour-intensive, it is most effective in lowering heat losses and increasing the air tightness of the building.

One of the starting points of the retrofit must be that in all the packages the indoor climate is improved and after the renovations better thermal comfort and good air exchange rate is ensured. The natural stack effect ventilation needs to be replaced with a mechanical balanced ventilation system with heat recovery. In the case of BAU, the mechanical exhaust ventilation system with air compensation through the fresh air valves solutions is used. Typically, the balanced ventilation with heat recovery is seen as too high investment because the initial cost is usually the most important factor for building owners. The energy savings gained by insulation measures are reduced because of the extra electricity consumption and an increased air exchange rate when mechanical ventilation without heat recovery is used. In historic buildings, often the space available for the ventilation system to be installed is limited. If the cost and energy savings are considered simultaneously, the second solution is more economical since a considerable amount of energy can be saved by installing a ventilation system with heat recovery.

To compare the cost-effectiveness of different renovation packages, the investment cost and energy costs were used. The interest rate of the investment was chosen based on the Estonian National Bank's statistics and from current market loan interest rates. The uncertainty of the interest rate and the escalation of the energy price is high, but it ultimately has the same effect in the retrofitted and reference building cases. Since the aim of the study was to compare the different retrofit scenarios, the energy and investment costs of energy renovation measures were considered. The comparison was done relative to a reference building, so the relative values are more relevant than the absolute figures. The repair and maintenance costs were taken into account in the calculation of the costs for the reference building.

Additionally, the indoor climate and thermal comfort were included in the calculations since it was assumed that all ECO and HER renovation packages include the installation of new heating and ventilation systems. If the energy consumption, cost, thermal comfort and other aspects are included in the optimization process, then all these criteria can have a diverse effect on the final result (Chantrelle et al. 2011). But in summary, insulating the building envelope and installing the new heating and ventilation systems will increase the thermal and living comfort in all the cases and have a positive effect in terms of the retrofit of existing buildings.

The results of the economic calculation in the case of the wood heating stove show that higher energy savings gained by combining different insulation measures do not increase the cost-effectiveness. The reason for the drop is the ratio between the cost and the gained energy savings. As more efficient renovation measures are more expensive, investment costs and interest charges will be higher. The change of the heat source seems to have a significant impact on both the cost and the PE of the renovation packages. Insulation measures combined with different heat sources result in a significant difference. Gustafsson (1998) and Verbeeck & Hens (2005) have additionally shown the importance of the heating system. The differences are relatively small between the WPB and GB heating. DH and AWHP show the highest ΔNPV values because of the high investment costs for the equipment. To reach the minimum requirement of 180 kWh/($m^2 \cdot a$), the lowest ΔNPV was found in the case of WPB and GB when the investment and the running costs did not exceed the running costs of the reference building. At the DH and AWHP, the cost-efficiency is exceeded. If the target is not set to meet the minimum requirement, the ΔNPV line stays well below zero, giving the opportunity to choose renovation packages depending on the desired PE with different heat sources and insulation measures.

There can be different renovation strategies to improve the energy efficiency of existing buildings: with BAU, -40% level was achieved without changing the heating system; with HER and ECO, -45% level was reached when the appearance was affected the least. To reach the EPV level set in the regulations in all the cases, the stove heating system has to be replaced by a new more efficient heat source and heating system. With BAU, the ventilation air change rate being 0.35 l/($s \cdot m^2$) and no heat recovery taken into account, the heat loss through air change has to be compensated for by adding a thicker layer of wall insulation to reach the PE level set in the regulations. If the ventilation air change rate is increased, the PE level set in the regulations is not reached. In the HER and ECO cases, the ventilation air change rate was 0.42 l/($s \cdot m^2$) and the ventilation system was with heat recovery. If heat recovery is taken into account, it leaves the possibility to use a thinner layer of thermal insulation in the external wall. Ventilation heat recovery has to be used if the characteristics and appearance of the building are taken into account. The ΔNPV values show that it is economically viable only to change the heat source and increase the efficiency of the heating system or implement the renovation package with the maximum insulation measures allowed. The risk of not using the optimal solution and the extra costs associated with the change of the heat source before the end of its lifetime exist. A whole simultaneous building retrofit is preferred, but often the large investments for the retrofit works can create obstacles. Therefore, the order of the renovation methods is important.

For the owners, the initial high cost of the major insulation measures can be a significant concern. Additionally, the costs of technical and bureaucratic issues can be obstacles to more energy efficient buildings, especially in the case of historic buildings. A conflict between the economically viable solutions and the sustainable conservation issues can emerge. The energy retrofit can be done in combination with renovation, replacement or other improvements to reduce the financing issue. In the near future, a serious need for extensive construction work occurs to preserve these historic wooden apartment buildings (Klõšeiko 2011). Improving the energy efficiency of building components at the time of retrofit and potential added value to the property (Popescu et al. 2012) can help to overcome the financing barriers. The willingness to make buildings more energy efficient can be increased if the minimum requirement of PE for the historic buildings and existing buildings subject to major renovation are considered separately. By reducing the PE, a wider range of renovation packages becomes available. The ΔNPV value curves indicate that the cost optimal PE of 250 kWh/(m^2·a) could be considered in the historic wooden apartment buildings. Renovation grants should apply for cases of lower energy use that are economically less attractive.

5.3 Hygrothermal performance of the interior insulation

5.3.1 Measurements

The test walls studied were located in apartments with high humidity loads. This was caused mainly due to lower indoor temperature and low air change rate (natural ventilation) because the heating and ventilation systems were not renovated.

The measurement results of the temperature and RH of the internally insulated walls resulted in high humidity levels that were favourable for mould growth on wooden material more than 75% of the measured time length. High RH levels between the insulation material and the log layer corresponded to the calculated steady-state winter conditions where the partial vapour pressure in the wall between the insulation material layer and the log layer exceeds the saturation pressure level. The interior insulation of the wall could be used if the vapour pressure inside the wall is lowered. Therefore, by installing a mechanical ventilation system, the moisture excess inside the room has to be reduced or by adding vapour retarding foil to the warm side of the insulation layer, the diffusion resistance is increased.

Insulation material (hygroscopic or not) did not significantly lower the risk for mould growth. Different test walls were separated by metal battens and polyurethane foam tightening to prevent diffusion and conduction between the test walls. Although there may have been some minor leaks between the test walls, the potential for the diffusion and conduction was low and possible heat and moisture movement between the test walls was probably minor.

Field measurements showed a high humidity level inside the internally insulated log wall. Hygrothermal conditions on the surface of the log wall between the log and additional insulation were favourable for mould growth in all the test walls. In this case study, this risk was also measured. The results showed that interior thermal insulation is a risky solution for wooden structures.

5.3.2 Simulations

Using the measurement results, the simulation model in WUFI was calibrated for further studies. The quality of the simulation results depends on the input variables, on the assumptions and simplifications made and on simulation settings. Hygrothermal performance simulations using HAM simulation programs may contain different kinds of errors beginning with the description of the existing wall assemblies to the chosen material properties in the case of retrofitted building constructions. In the studied walls, the hygrothermal properties of wood play an important role, because the log layer is a geometrically dominating material. Including or excluding the capillary flow in the simulations affects the calculation results. Including the capillary flow in the simulation model improved the calculation results. Dividing the total moisture flow between diffusion and capillary flow, may cause errors without knowing the exact properties of the material. No laboratory tests were conducted to obtain the data about the properties of the different building materials used in the existing wall construction. The material database of the simulation tool and material data from the literature were used. The hygrothermal properties of the building materials not described in the material database were entered into the program based on the results from the literature. The hygrothermal properties of different species of wood vary considerably. Properties may also vary because of the age of the wood and history of the climate conditions the wood has been exposed to. There is a need of information about the possible changes in material properties during the ageing. To acquire more reliable calculation results, the material properties should be determined by laboratory tests.

The air change rate in the material layers was also noticed to have an effect on the calculation results. The air change rate was considered to be the moisture flow affecting factor connected to the air tightness of the existing log wall and was equal in simulation models with different insulation materials. The air change rate was introduced as a constant during the whole calculation period. This can cause an error because in real life it is not constant due to the variable temperature gradient and wind.

The first calculated RH values excluding the capillary flow were much higher than the measured RH levels inside the wall between the log layer and the insulation if the material properties from the WUFI database were used. It also occurred when the capillary flow RH levels were higher than the measured values. After entering the air change rate into the simulation model the calculated RH levels were higher than the measured results. The calculated results show the riskiness of the internal insulation if the hygrothermal performance of the retrofitting solution has to be assessed. The situation would be worse if the calculation results were smaller than the measured values. Then there would be a possibility of making a wrong decision on using internal insulation as the retrofitting solution.

5.3.3 Assessment of moisture safety of interior thermal insulation

The study contains simplifications and assumptions. It should be noted that a probabilistic study needs a realistic input. The applied retrofit measures are assumed to be installed in good quality, i.e. no workmanship errors were taken into account. The simulations were done using a 1-d simulation model, no leakages due to construction junctions or other possible cracks were taken into account.

For probabilistic distribution characteristics, the normal distribution is used for indoor temperature and moisture excess. For thermal conductivity of the insulation material, uniform distribution (min, avg, max) of the insulation material and log layer thicknesses is used to avoid preferring any certain values or value ranges. As a simplification, one type of vapour barrier (Z_p=0.96 (m^2•s•Pa)/kg; μ=190) was considered as installed or not (yes or no). "No" describes also a situation if the barrier is broken.

The Spearman correlation (ρ) is used to evaluate the rank correlation between *M index* values (randomly generated simulation cases) calculated in the first step and the probabilities (based on the regression coefficients) calculated in the second step. Spearman ρ assesses how well the relationship between the two variables can be described using a monotonic function. The critical values of the Spearman's correlation coefficient are presented by Zar (1972). For the probability of 0.0005 that the correlation occurred by chance, the critical value ρ≥0.326 (sample size *n*=100). Values of the Spearman correlation close to 1 or -1 indicate high correlation between the compared indicators and values close to zero indicate low correlation. For the correlation between the *M indexes* and the probabilities, the Spearman correlation indicates high monotony (ρ>0.82).

In this study the mould growth index is considered as the performance indicator for risk assessment. In (Sanders 1996) the use of 10% percentile as the critical level for the hygrothermal dimensioning of the building envelopes is recommended, i.e. "normative" value should not appear in more than 10% of the cases. According to (WHO 2009), mould is one of the most hazardous contaminants of the indoor air and has to be prevented in any circumstances. Presently, no generally accepted agreements on the acceptable failure % exist for the risk assessment in the case of mould growth. It is crucial to set the acceptance criteria taking into account the risks to occupants and the risks regarding the economic aspects. If we can take risks considering economic aspects, then we cannot risk with people's health. But in both cases, even if the acceptable limit is set at 10%, the probability of the interior insulation to fail is too high. To lower the risk of failure, the design values of the retrofit solution have to be changed and analysed more deeply in further studies. It is required to take preventive measures appropriate to interior insulation. It can be assumed that concerning thermal insulation, thinner material layer or materials with higher thermal conductivity should be considered compared to base case. In addition, reduced moisture excess (ventilation system) and proper indoor temperature (heating system) are of high importance to ensure the performance of the interior insulation. Therefore, considering interior insulation as a retrofit measure, it must be installed in combination with properly functioning ventilation and heating systems.

5.4 Milieu values

This study showed that it is possible to take into account milieu values in the energy renovation of historic wooden apartment building

Within the determination of the need for renovation (thermal comfort, energy performance), grades were given to the renovation solutions, based on their influence on the milieu values. When the whole building is under renovation all at once, it is possible to guarantee that all materials, relationships between different building structures and elements can be preserved and only minor changes influence the milieu of the district.

The starting condition of the building has a strong influence on the overall grade of the renovation measures. To gain moderate savings, out of single or couple insulation measures, the measures less visible should be preferred. Under larger energy savings, by applying few measures, a major change of the influence occurs when the external thermal insulation is considered without any changes in other constructions or junctions connected to the external wall. But in both cases the whole building renovation is preferred when the energy savings are larger and the overall influence on the milieu value is smaller. The reason is that when renovating the whole building, all the different parts of the building are taken into account and it is easier to solve the junctions of the façade elements without degrading the architectural appearance of the building.

6 CONCLUSION

The indoor climate and energy performance of the historic wooden apartment buildings was analysed by field measurement and computer simulations. In historic wooden apartment buildings, the measured primary energy (PE) use was 331 kWh/(m^2·a), which is 25% higher than PE use in typical brick apartment buildings and 84% higher than the minimum energy performance requirement for the buildings subject to major renovation in the energy performance regulation (EPV≤180 kWh/(m^2·a)) in Estonia. It was found that the requirement of major renovation (EPV≤180 kWh/(m^2·a)) is achievable if the new energy source is combined with the attic floor insulation, cellar ceiling insulation and with new windows or exterior wall insulation. A maximum of 63% reduction was achieved in the case of the pellet boiler heat source with a heat recovery ventilation system, and with all the maximal insulation measures considered. The investment costs of renovation measures and energy costs were used to compare the effectiveness of different renovation packages. The results of the economic assessment showed that higher energy savings from different insulation measures combined, without considering the building service systems do not increase the cost-effectiveness. Combining insulation measures with building service systems broadens the possibilities and higher energy savings can be achieved in an economically viable way. Considering the construction work needed to preserve the buildings and helping owners to overcome the technical and economic barriers can result in more active retrofitting, and as a result in higher energy savings.

The results of the measured indoor temperature reveal a linear dependency on the outdoor temperature, showing two times larger deviation than at higher outdoor temperatures. Indoor temperature was outside class III target values in 83% of the apartments in winter and in 25% of the apartments in summer. Indoor temperature variations reflect also the complaints concerning the unstable temperature and cold floors during the winter period. The indoor climate conditions differ from those in more recent apartment buildings and it is necessary to improve the indoor thermal comfort. Even though most of the time the thermal comfort is outside the acceptable moderate level of expectations, the building occupants showed overall satisfaction with the living environment in historic wooden apartment buildings.

For the hygrothermal analyses of the building envelope, the modelling curves of the indoor temperature and the moisture excess were derived from the measurement results. The curves of the indoor temperature and the moisture excess reveal the dependence on an average value and a standard deviation value on the outdoor temperature. The presented curves can be used for stochastic analysis with the dynamic simulations of the hygrothermal performance.

Even the interior thermal insulation seems to be a possible solution when the external style has a high value and must be preserved, the solution should be carefully analysed in order to prevent occurrence of hygrothermally critical conditions. In the studied case, the durability of the renovation solutions was questionable because the measurement results showed inadequate hygrothermal performance of the internally insulated log wall. In addition, the high risk of mould growth led to mould problems that caused health problems for the inhabitants of the apartment.

In further studies, a good correlation between the measured values and the simulated results was achieved. To determine drying and wetting more accurately, material's properties were modified and a factor of air change rate in the material's layers inside the wall was added. The validated model was used to analyse the performance of the interior insulation in cold climates using the probabilistic approach. The reliability analysis about of the interior thermal insulation as a retrofit measure was done. As the results of the stochastic study of the test walls show, a solution that involves design values with possible distributions considered is unreliable for the interior insulation.

In the near future, large numbers of buildings in the milieu valuable areas will require renovation. A method to assess the influence of energy retrofit measures on the building level in the milieu valuable district was introduced and tested. Different renovation packages were analysed to find possible changes the in building appearance. Independent of the starting conditions, the whole building renovation is preferred over single insulation measures that are visually easier to detect. Our results show that the energy performance of the historic wooden apartment buildings can be improved significantly without negative influence on the architectural appearance and destroying the milieu value of the district.

Even directive and national legislation provides an exception for buildings with special architectural or historical merit. It seems to be fully justified that owners and inhabitants have increased interest and willingness to invest in energy saving solutions to decrease expenses for energy, to make renovation more cost effective and to live in a more environmentally friendly building. To achieve the goal, future studies are needed to cover reliability issues to set the acceptance criteria taking into account the risks to occupants and the risks regarding the economic aspects. Also, the inhabitants' and building owners' real attitude towards energy retrofit should be studied.

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Sünniaeg ja -koht 08.03.1978 Tallinn

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Hariduskäik

Õppeasutus	Lõpetamise aeg	Haridus (eriala / kraad)
Tallinna Tehnikaülikool	2009	Keskkonnatehnika / tehnikateaduste magistri kraad
Tallinna Tehnikaülikool	2003	Keskkonnatehnika / tehnikateaduste bakalaureuse kraad

Keelteoskus (alg-, kesk- või kõrgtase)

Keel	Tase
eesti	emakeel
inglise	kõrgtase
soome	kõrgtase
vene	kesktase
rootsi	algtase

Täiendusõpe

Õppimise aeg	Täiendusõppe korraldaja
09.2012 - 05.2014	Külalisteadur, Gotlandi Ülikool, Lundi Ülikool, Rootsi
04. - 12.2011	Moisture in materials and structures. Lundi Ülikool, Rootsi
09. - 14.01.2011	Urban Physics Winter School 2011. Ascona, Šveits
13. - 16.12.2010	Net-zero-energy-buildings and on-site renewable energy, Aalto Ülikool, Soome
18. - 22.10.2010	Short course on microclimate monitoring. Padua Ülikool, Itaalia
17. - 18.02.2010	Solar Energy Systems, Tallinna Tehnikaülikool

Teenistuskäik

Töötamise aeg	Tööandja nimetus	Ametikoht
2010 -	Tallinna Tehnikaülikool	Teadur
2009 - 2010	Tallinna Tehnikaülikool	Assistent
2006 - 2009	Kuupmeeter OÜ	Insener
2003 - 2006	Insinööritoimisto Akukon Oy Eesti Filiaal	Konsultant
2001 - 2003	BI Inseneribüroo OÜ	Insener
1999 - 2001	AS TRV Kliima	Tehnik
1997 - 1999	AS Clik	Tehnik

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Education

Educational institution	Graduation year	Education (field of study/degree)
Tallinn University of Technology	2009	Environmental Engineering / Master of Science
Tallinn University of Technology	2003	Environmental Engineering / Bachelor of Science

Language competence/skills

Language	Level
Estonian	Native
English	Fluent
Finnish	Fluent
Russian	Average
Swedish	Basic

Special courses

Period	Educational or other organisation
Sept.2012 - May.2014	Visiting researcher, Gotland University, Lund University, Sweden
Apr. - Dec.2011	Moisture in materials and structures. Lund University, Sweden
09. - 14.01.2011	Urban Physics Winter School 2011. Ascona, Switzerland
13. - 16.12.2010	Net-zero-energy-buildings and on-site renewable energy, Aalto University, Finland
18. - 22.10.2010	Short course on microclimate monitoring. Padua University, Italy
17. - 18.02.2010	Solar Energy Systems, Tallinn University of Technology

Professional employment

Period	Organisation	Position
2010 -	Tallinn University of Technology	Researcher
2009 - 2010	Tallinn University of Technology	Assistant
2006 - 2009	Kuupmeeter Ltd.	HVAC system designer
2003 - 2006	Akukon Engineering Ltd. Estonian branch	Consultant (acoustics, noise)
2001 - 2003	BI Inseneribüroo Ltd.	HVAC system designer
1999 - 2001	TRV Kliima Ltd.	HVAC engineer
1997 - 1999	Clik Ltd.	HVAC engineer

Publications

Articles in pre-revived scientific journals

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III Arumägi, E., Kalamees, T., Pihlak, M. (2015). Reliability of interior thermal insulation as a retrofit measure in historic wooden apartment buildings in cold climates. Energy Procedia 00 (2015) 000–000.

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Analysis of energy economic renovation for historic wooden apartment buildings in cold climates

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HIGHLIGHTS

- Energy saving potential in historic wooden apartment buildings is up to 63%.
- In historic wooden apartment buildings an economically viable energy saving level is 50%.
- The largest energy saving potential lies in heat source and building service systems.
- Of the building structures, insulation of the external wall has the highest potential.
- New heating and ventilation systems must be installed to fulfill regulations limits.

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ABSTRACT

Buildings represent the largest sector of primary energy consumption and play a major role in saving energy and reducing greenhouse gas emissions. Our analysis of energy consumption and potential energy savings is based on field measurements, computer simulations and economic calculations. The average primary energy consumption (PE) of wooden apartment buildings was 331 kW h/(m^2 a) 83% higher than the limit 180 kW h/(m^2 a) set in national regulations for apartment buildings subject to major renovation. The studied buildings represent a high potential for energy savings. The renovation packages were compiled using different insulation measures, HVAC solutions and energy sources to achieve a 20–65% reduction of primary energy. For historic buildings, the renovation solutions that concentrate on the building envelope can be problematic due to the need to preserve cultural and architectural values. Our calculation results indicate that the cost optimal PE level is around 250 kW h/(m^2 a) and the point at which renovation packages recover expenses is around a PE level of 170 kW h/(m^2 a). In terms of the architectural appearance the point at which renovation packages recover expenses is around a PE level of 210 kW h/(m^2 a). We propose to set a different PE limit for historic wooden apartment buildings with an architectural appearance worth preserving.

1. Introduction

Buildings represent the largest sector of primary energy consumption and play a major role in saving energy and reducing greenhouse gas emissions. Improvements of apartment buildings have raised their inhabitants' awareness of energy consumption in the building and have increased willingness to invest in energy saving solutions. Results [1–3] have indicated that the main savings potential lies in the improvement of the building's shell of existing building stock. Research by Altan and Mohelnikova [4] underline the importance of such thermally insulated building envelopes together with new windows for the reduction of overall energy consumption. It was shown by Morelli et al. [5] that theoretical energy use can be reduced by 68% as compared to the energy use prior to the retrofit by the installation of insulation, new windows and a ventilation system with heat recovery.

For historic buildings, the renovation solutions that concentrate on the building envelope are problematic due to the need for preserving cultural and architectural values. For historic, heritage, and traditional buildings, the improvement of energy performance should be a special case [6]. The energy savings in historic buildings are a new research challenge [7]. In addition to the analysis of the building's energy saving potential and its influence on the architectural appearance, economic viability [13–15] is an essential issue because the cost of the measures varies according to the type of the measure, the type of the building, individual conditions and the circumstances of the renovation.

Many studies discuss energy renovation of apartment buildings in scale from building components [8–11] through single buildings [12–14,16,17] up to full building stock [18–24]. Studies of

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energy-renovation have concentrated on historic apartment buildings [5,6,25,26] rather than on the energy-saving potential of historic wooden apartment buildings. This study discusses the technical potential and economic impact of potential energy renovation solutions for historic wooden apartment buildings in the Northern European cold climate in Estonia.

2. Methodology

We combined here field measurements, computer simulations and financial calculations of energy renovation measures.

2.1. Studied buildings

The study concentrates on the historic wooden apartment buildings that were built before the Second World War. They are a mark of industrial development and general urbanization in the history of Estonia.

Altogether 29 buildings and 41 apartments were investigated. Apartments in a typical historic three-story wooden apartment building consist of up to three rooms, with a separate kitchen, entry and sanitary rooms. The basement floor typically houses storerooms or rooms for small businesses. Fig. 1 shows the appearance and the floor plan of one of the reference buildings.

The chosen buildings occupy a volume of about 490–980 m^3, the heated area of the buildings was between 242 and 823 m^2 and the average age was 98 years. Fig. 2 shows the cumulative distribution of the closed net area and the living space area of wooden apartment buildings in Estonia.

The external walls are typically made of 120–160 mm thick logs, without additional insulation, covered with wooden cladding or render. The attic floor is filled with a mix of the sand and sawdust as insulation materials. The buildings have two-pane windows with wooden frames. In 65% of the buildings, the apartments were heated by a wood heating stove (original) and in 35% by radiators (new). The heat source for the radiator system was mainly electricity or a gas boiler and in one of the buildings district heating. Most of the buildings were equipped with an electrical boiler to heat the domestic hot water. The studied dwellings had natural passive stack ventilation.

For our simulations, four buildings were selected as reference buildings based on the size and representativeness of a typical historic wooden apartment building from the era before the Second World War. All the buildings have simple floor plan with a central staircase made of stone in buildings “B” and “C” and made of wood in buildings “A” and “D”. Building “D” has no basement and the 1st floor is on the ground, buildings “A” to “C” are with a basement floor. Key characteristics describing the size and shape of the reference buildings are presented in Table 1.

2.2. Field measurements

Field measurements included indoor climate studies [28], building surveys and measurements of the properties of the building’s envelope [29]. Data for the electricity, gas, district heating and water consumption for each building were collected from the suppliers on a monthly basis over a three to four year period. The consumption of the firewood for heating was obtained from the apartment owners. In the absence of more accurate data, the energy used for heating in the buildings was estimated based on the information about the wood consumption in the apartments. The energy consumption of the buildings was analyzed, based on collected data, to give an overview of the real energy use in historic wooden apartment buildings in cold climates.

2.3. Simulations

The multi-zone indoor climate and energy simulation program IDA Indoor Climate and Energy 4.5.1 (IDA ICE) [30,31] was used for the simulations. The simulations were used to calculate the energy consumption of the buildings, to predict the energy savings and to propose the retrofit measures. Validated in different studies [32–35], IDA ICE is a tool for building simulations of energy consumption, indoor air quality and thermal comfort.

Simulation models were calibrated based on field measurements, user behavior, measured indoor climate and air tightness results. The energy renovation measures were simulated with the standard use of the building (indoor temperature ($\geqslant$21 °C); ventilation airflow (0.42 l/(s m^2) (normal level of expectation: indoor climate category class II [36] per heated area); the usage rate of the building, lightning (8 W/m^2) and equipment (2.4 W/m^2); and the heat from the inhabitants (2 W/m^2) to reduce the influence of the user behavior. For outdoor climate, the Estonian test reference year (HDD 4160 °C/d at t_i + 17 °C) [39] was used. In our calculations, delivered energy efficiencies of energy production and heat distribution systems were taken into account (see Table 2).

In our calculation of primary energy usage (presented as the energy performance value EPV, kW h/(m^2 a), the delivered energy is multiplied by the weighting factors for energy carriers:

- wood and wood-based fuels (excl. peat and peat briquettes) : 0.75;
- district heating: 0.9;
- fossil fuels (gas, oil, coal): 1.0;
- electricity: 2.0.

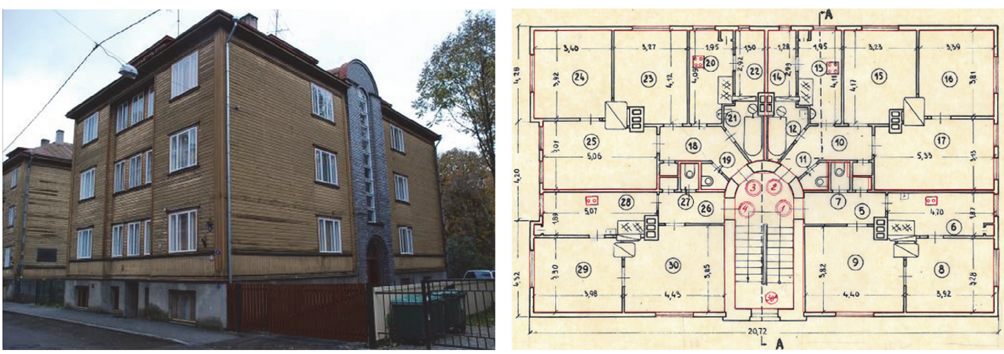

Fig. 1. Street view and the floor plan of a typical wooden apartment building (reference B).

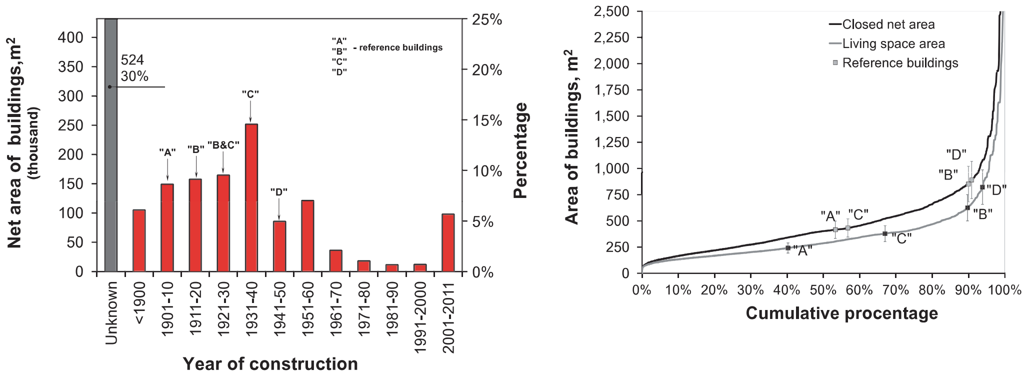

Fig. 2. Distribution of closed net area and construction year (left); cumulative percentage of the net area and living space area of whole stock of wooden apartment buildings and the reference buildings (right).

Table 1
Key characteristics of the simulated reference buildings.

Characteristics	Reference building			
	"A"	"B"	"C"	"D"
Number of floors[a]	2 + 1	3 + 1	2 + 1	2
Number of apartments	10	12	8	16
Area under building, m^2	170	269	183	506
Closed net area, m^2	416	852	433	891
Heated area, m^2	295	672	283	823
External wall area, m^2	370	667	469	467
Area of windows and doors, m^2	68	122	49	153
Ratio of external wall area and heated volume, m^{-1}	0.76	0.68	0.79	0.65
Thermal transmittance of building envelope U, W/(m^2 K)				
External wall	0.65	0.65	0.57	0.51
Basement wall	1.46	1.45	1.31	–
Windows	2.9	2.9	2.9	2.9
Attic floor	0.50	0.42	0.59	0.66
Basement floor	0.50	0.52	0.53	0.46
Air leakage rate of building envelope q_{50},m^3/(h·m^2)	5.6	7.5	11.1	10.3

[a] 2 + 1 means total of 3 floors (2 floors with apartments and basement floor).

2.3.1. Energy renovation measures

The reference case is a building with its original structure, stove heating and natural passive stack ventilation. Energy renovation measures were applied to the building envelope (facade, attic floor, windows-doors, and basement floor) and the building's service systems (heating, ventilation, energy source). The thickness of additional insulation for the facade (λ = 0.04 W/(m K)) varied between 20...270 mm, for the attic floor 100...400 mm and for the basement floor 100...200 mm. Four renovation measures for windows were considered from the renovation of original windows (U 1.8 W/(m^2 K)) up to the installation of new windows (U 0.8 W/(m^2 K)).

Table 2
Efficiency of heat production and distribution systems.

	Efficiency (–)	
	Room heating	Domestic hot water
Energy production		
Wood burning stoves (original) (WBS)	0.6	
Wood-pellet boiler (WPB)	0.85	0.85
Oil condensate boiler (OB)	0.9	0.9
Electricity (EL)	1.0	1.0
District heating (DH)	1.0	1.0
Gas boiler heating (GB)	0.95	0.95
Air–water heat pump (AWHP)	2.4	1.8
Heat distribution		
Wood burning stoves	0.85	
Hydronic radiators	0.97	
Electric radiators	1.0	

2.4. Economic assessment of renovation measures

The economic effect of renovation measures was assessed through a balance of investment cost and energy savings. Global cost (the net present value (NPV), considering the investment cost over a 20 year period) was used to assess the economic effect of renovation measures [40]:

$$C_{G(\tau)} = C_i + \sum_{i=1}^{20}((C_{a,i} + C_{l,i}) \cdot R_d(i)) \quad (1)$$

where $C_{G(\tau)}$ is the global cost, NPV, €; C_i is the initial investment cost €; $C_{a,i}$ is the annual energy cost i €; $C_{l,i}$ is the annual loan interest rate cost i €; $R_d(i)$ is the discount factor for the year i €.

Renovation measures were assessed based on the difference of NPV (ΔNPV) of the reference case and the renovated case:

$$\Delta NPV = (C_G - C_G^{ref})/A_{floor} \quad (2)$$

where C_G is the global cost of the building in the renovated case (€); C_G^{ref} is the global cost of the building in the reference case (€); A_{floor} is the heated net floor area of the building, m^2.

The real interest rate was 4% and a 3% annual escalation of energy price was used in our calculations. The initial investment cost includes construction works and the components: additional thermal insulation with finishing, windows, air handling units and heat supply solutions with the required duct and pipe works. Prices for the different parts of the construction works were obtained from the construction companies. The construction costs included labor costs, material costs, overhead, the share of project management and value added tax. Discounted energy cost included all annual costs related to heating and electricity energy consumption. The prices for the energy carriers were obtained from the suppliers' info:

- heating wood (billet) 37.7 €/MW h;
- pellet 39.6 €/MW h;
- natural gas 47.4 €/kW h;
- district heating 68.3 €/kW h;
- electricity 118.0 €/MW h.

3. Results

3.1. Measured energy consumption

To give an overview of the real energy use in historic wooden apartment buildings in cold climates the energy consumption of the buildings was analyzed based on field measurements.

The overall electricity consumption includes lighting, electric appliances and in some buildings also domestic hot water and space heating. In the studied buildings, the annual average of overall electricity consumption was 58 kW h/(m^2 a) with a minimum of 27 kW h/(m^2 a) and a maximum of 107 kW h/(m^2 a).

The average electricity consumption in the studied buildings was 58 kW h/(m^2 a) (different buildings 26…103 kW h/(m^2 a)). Because of electricity consumption for hot water heating in most cases and for heating in some cases the average electricity usage was above 30 kW h/(m^2 a) that represents electricity use in standard conditions [38] and was used in our energy performance calculations.

The annual total water usage was 986 l/(m^2 a) (st.dev. 329 l/(m^2 d)) and 72 l/(person d) (st.dev. 21 l/(person d)). The domestic hot water usage was 410 l/m^2 a (st.dev. 130 l/m^2 a), which is 40% [41] of the total water consumption. The annual average energy usage for domestic hot water heating was 36 kW h/(m^2 a) (st.dev. 11 kW h/(m^2 a)), taking into consideration that water is heated up from 5 °C to 55 °C.

Gas was used for space heating, for domestic hot water and for cooking. The overall annual average usage of gas was 16.3 m^3/(m^2 a) (st.dev. 9.3 m^3/(m^2 a)). Average consumption of gas was 21.6 m^3/(m^2 a) in buildings where gas was used for the domestic hot water and room heating system.

The average heating energy used was 211 kW h/(m^2 a) (st.dev. 68 kW h/(m^2 a)) adjusted to the reference year based on heating degree-days (HDD) at a balance temperature of +17 °C. The energy consumption was calculated using the calorific values 9.3 kW h/m^3 for natural gas, 1300 kW h/(stack m^3) for firewood, 4.6 kW h/kg for wood briquette and 4.2 kW h/kg for peat briquette.

The total primary energy consumption includes the heat and fuel consumption for heating, air change and infiltration, domestic hot water as well the electricity for lighting, electrical appliances and technical systems. The average primary energy consumption was 331 kW h/(m^2 a) (st.dev. 72 kW h/(m^2 a)), Fig. 3 left. From the studied buildings, 60% fulfilled the requirements for the energy performance certificate (EPC) class "G" (9 buildings), 27% for class "F" (4 buildings) and 13% for class "E" (2 buildings). The average distribution of energy was 50% for heating, 36% for electricity (lighting, electric appliances) and 14% for domestic hot water, Fig. 3 right.

3.2. Simulations

3.2.1. Energy balance and energy savings of different renovation measures

To show the influence of single renovation measures, the delivered energy (DE) and primary energy consumption (PE) simulations were done using renovation measures one at a time and comparing the result to the reference case. District heating (DH), a gas condensing boiler (GB), a pellet boiler (WPB) and an air to water heat pump (AWHP) as new heat sources with hydronic radiators were compared with existing wood heating stoves (see Table 3).

Fig. 4 compares different single energy-renovation measures taking into account the change of the primary energy use and the global cost. A clear turning point can be seen in the cost optimal curve of different renovation measures. Some of the renovation measures can be considered expensive in terms of the amount of energy saved by implementing the renovation measure.

3.2.2. Energy saving packages

In the second step, the renovation packages were combined using single renovation measures. The results are presented in three different groups: packages according to current renovation practice (BAU), the packages that alter the architectural appearance the least to save heritage buildings (HER), and packages with the best economic effect (NPV). These three can be seen as representative of the different attitudes of different building owners. The packages are presented to attain different energy savings from −20% as a minimum primary energy saving to −55% as PE requirement for existing buildings that are subject to major renovation; and "max" as the lowest PE consumption of simulation cases (see Table 4). In the BAU case the mechanical exhaust ventilation system with the air compensation through the fresh air valves is considered in the indoor climate category III [36]: 0.35 l/(s m^2). In the cases of HER and NPV the new mechanical exhaust-supply ventilation system with heat recovery is considered together with the improvement of air flows to the indoor climate category level II [36], from 0.35 l/(s m^2) to 0.42 l/(s m^2).

3.3. Economic assessment of the renovation packages

The energy saved long-term as a result of retrofit lowers the annual energy costs. The costs are adjusted to current Euro values and are used to compare the renovation packages. If the latter is equal to or smaller than the reference case, the renovation measure can be considered economically viable. The results for different building types vary to a large degree. If the results are divided into groups according to the heat source, then the average curves can be drawn to see the differences between the renovation packages. The curves in Fig. 5 indicate clearly how the heat source influences the possible energy savings and future annual energy costs. The starting point of the curve shows the lowest energy savings as per different heat sources. The limit of 180 kW h/(m^2 a) for the buildings under major renovations can be achieved only if the wood-burning stove heating is replaced for a new heating system. Comparing the ΔNPV, only the pellet and the gas boiler are on the negative side and therefore can be considered economical.

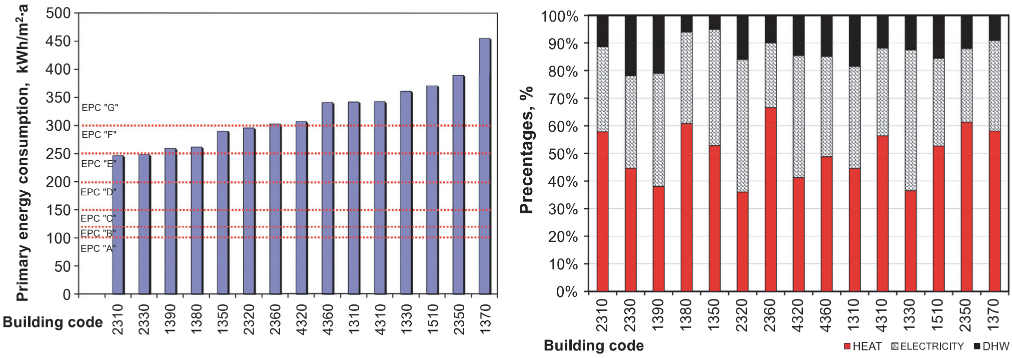

Fig. 3. Primary energy consumption of the buildings and distribution between heating, electricity and domestic hot water.

Table 3
Influence of single energy renovation measures.

Energy-renovation measures	DE		PE	
	Average/range (kW/(m² a))	Decrease from base case (%)	Average/range (kW/(m² a))	Decrease from base case (%)
Base case				
Original structures, stove heating + exhaust ventilation + electricity for DHW	449/369…517	0	416/353…463	0
Improvement of building envelope				
AF200. Attic floor/roof: +200 mm insulation: *U* 0.17 W/(m² K)	414/332…479	−8	390/325…435	−6
AF400. Attic floor/roof: +400 mm insulation: *U* 0.11 W/(m² K)	408/326…473	−9	385/321…430	−7
BF100. Basement ceiling: +100 mm insulation: *U* 0.21 W/(m² K)	434/363…498	−3	404/349…448	−3
EW20. External wall + 20 mm insulation: *U* 0.51 W/(m² K)	428/351…489	−5	400/339…442	−4
EW70. External wall + 70 mm insulation: *U* 0.34 W/(m² K)	401/334…456	−11	380/327…417	−9
EW120. External wall + 120 mm insulation: *U* 0.24 W/(m² K)	386/325…441	−14	369/320…406	−11
EW170. External wall + 170 mm insulation: *U* 0.19 W/(m² K)	377/321…429	−16	362/317…397	−13
EW220. External wall + 220 mm insulation: *U* 0.13 W/(m² K)	372/319…423	−17	363/319…398	−14
W1.8. Window renovation: *U* 1.8 W/(m² K)	421/345…481	−6	395/335…436	−5
W1.4. Window replacement: new *U* 1.4 W/(m² K)	416/340…474	−7	391/331…431	−6
W1.1. Window replacement: new *U* 1.1 W/(m² K)	404/331…462	−10	382/324…422	−8
W0.8. Window replacement: new *U* 0.8 W/(m² K)	394/321…451	−12	374/317…414	−10
Improvement of HVAC systems				
HR60. Balanced ventilation with heat recovery 60%	394/314…454	−12	384/320…428	−8
HR80. Balanced ventilation with heat recovery 80%	365/281…438	−19	362/295…415	−13
DH. district heating for room heating, ventilation and DHW	240/202…270	−46	272/234…299	−35
GB. gas boiler heating for room heating, ventilation and DHW	251/211…282	−44	283/243…312	−32
WPB. pellet boiler for room heating, ventilation and DHW	277/232…312	−38	248/214…271	−40
AWHP. air to water heat pump for room heating, ventilation and DHW	132/114…145	−70	264/228…290	−36

An economically optimal solution is assumed to be achieved if the ΔNPV is the lowest. The lowest ΔNPV for different packages with different heat sources is presented in Fig. 5. Small grey dots show the distribution of all the results of the simulated cases of the different reference buildings. The colored dots show the average of different reference buildings with the same heat source and renovation measures. The curve for the minimum ΔNPV is combined with the different renovation packages with different heat sources. The curves stay on the negative side for a wide range, indicating that renovation packages can be economically viable if a new heating system is considered.

The minimum NPV curve stays below the zero line offering a wide range of opportunities to choose the renovation packages depending on the desired PE with different heat sources and insulation measures. In the case of the historic buildings with the facades that are worth preserving and a desire to keep the characteristics, the renovation measures affecting the appearance the least have to be considered first. Fig. 6 shows the differences between the renovation packages when the architectural appearance of the building is considered in comparison with the current renovation practice and the highest economical effect. In the case of BAU, stove heating is considered, and in the cases of HER and NPV, the curves are presented as an average of the different heat sources.

4. Discussion

Our study is limited to historic wooden apartment buildings. The calculated EPV of all the studied buildings was higher than the limit set for existing buildings subject to major renovation presented in [37]. In most of the buildings the average electricity and water consumption was below the level used to calculate the PE consumption in standardized use. If the energy used for hot water heating is subtracted, then 75% of the buildings will consume less than 30 kW h/(m² a) that was used in our energy performance

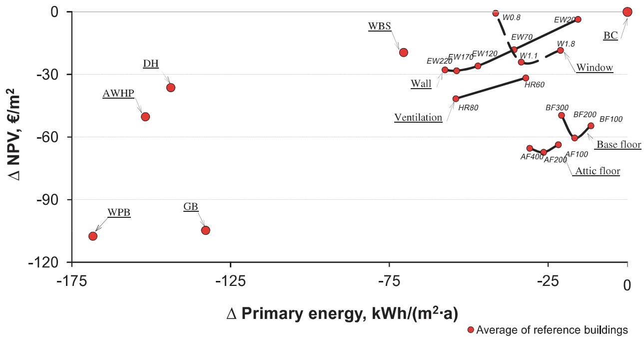

Fig. 4. The economic impact of different renovation measures.

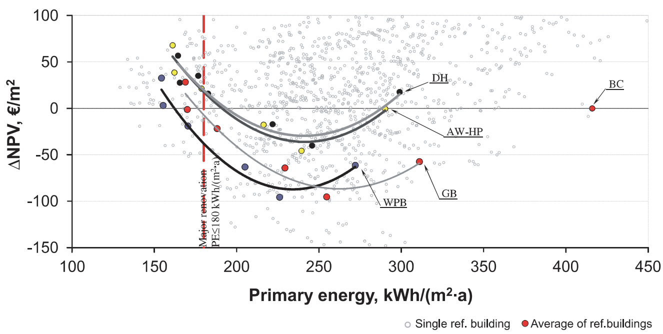

Fig. 5. Minimum NPV with different heat source.

Table 4
Primary energy consumption, savings and economic assessment of the renovation packages.

Renovation packages		Attic: AF 200	Attic: AF 400	Floor: BF100	Window: W1.8	Window: W1.1	Window: W0.8	External wall: EW20	External wall: EW70	External wall: EW120	External wall: EW170	Service systems: WBS new	Service systems: HR80%	Service systems: New heatsource	PE: kW h/(m² a)	PE: % of savings	ΔNPV: +3% energy price	ΔNPV: +5% energy price
−20%	BAU		x	x	x				x						318	23	−3	−21
	HER											x	x		308	26	−20	−39
	NPV	x		x									x		323	22	−24	−40
−35%	BAU		x	x		x			x						262	37	22	−5
	HER		x	x									x		270	35	12	−12
	NPV													x	267	36	−75	−98
−55%	BAU		x	x		x					x			x	193	56	40	5
	HER		x	x			x	x					x	x	174	58	1	−39
	NPV		x	x		x			x				x	x	174	58	22	−20
MIN PE			x	x			x				x		x	x	162	61	46	2

calculations. The average domestic hot water consumption below 520 l/(m^2 a) was used in our energy performance calculations. Overall 76% of the buildings studied used less than 520 l/(m^2 a). The PE and the distribution between different systems reveal a great potential for heating energy savings.

The key to energy savings is in the reduction of the heat losses through the building envelope. Heat losses can be reduced by adding insulation to the external walls, floors or roof, replacing the glazing or changing the windows. In addition in historic wooden apartment buildings, air tightness is an important aspect of energy efficiency. Therefore, improving the building envelope also has a positive effect in cases of air leakages and thermal bridges. As the study made by Homb and Uvsløkk [42] shows, instead of replacing existing windows, they can be made more energy efficient. Though adding insulation to the external wall is most labor-intensive, it is most effective in lowering heat losses and increasing the air tightness of the building.

One of the starting points of the retrofit must be that in all the packages the indoor climate is improved and after the renovations better thermal comfort and good air exchange rate is ensured. The

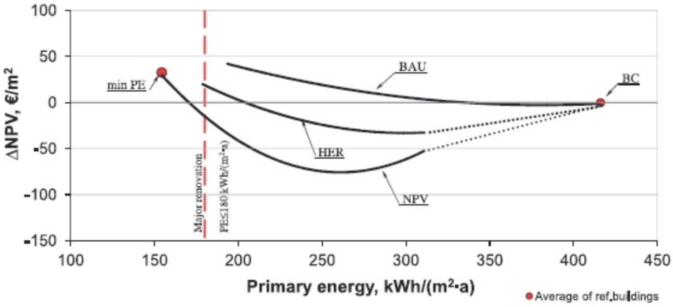

Fig. 6. Comparison of renovation packages considering different attitudes and requirements.

natural stack effect ventilation needs to be replaced with a mechanical ventilation system. The mechanical ventilation systems can be of two different types: the mechanical exhaust ventilation system with air compensation through the fresh air valves or the mechanical exhaust-supply system with a ventilation unit including heat recovery. In the case of BAU the first solutions is used. Typically, the second type of renovation is seen as too expensive because cost is the most important factor for building owners. The energy savings gained by insulation measures are reduced because of the extra electricity consumption and an increased air exchange rate when mechanical ventilation without heat recovery is used. In historic buildings often the space available for the ventilation system to be installed is limited. If the cost and energy savings are considered simultaneously the second solution is more economical since a considerable amount of energy can be saved by installing a ventilation system with heat recovery.

To compare the cost-effectiveness of different renovation packages, the investment cost and energy costs were used. The interest rate of the investment was chosen based on the Estonian National Bank's statistics and from current market loan interest rates. The uncertainty of the interest rate and the escalation of the energy price is high, but it ultimately has the same effect in the retrofitted and reference building cases. Since the aim of the study was to compare the different retrofit scenarios, the energy and investment costs of energy renovation measures were considered. The comparison was done relative to a reference building, so the relative values are more relevant than the absolute figures. The repair and maintenance costs were taken into account calculating the costs for the reference building.

Additionally, the indoor climate and thermal comfort were included in our calculations since we assumed that all NPV and HER renovation packages include the installation of new heating and ventilation systems. If the energy consumption, cost, thermal comfort and other aspects are included in the optimization process, then all these criteria can have a diverse effect on the final result [9]. But in summary, insulating the building envelope and installing the new heating and ventilation systems will increases the thermal and living comfort in all the cases and have a positive effect in terms of the retrofit of existing buildings.

The results of the economic calculation in the case of the wood heating stove show that higher energy savings gained by combining different insulation measures do not increase the cost-effectiveness. The reason for the drop is the ratio between the cost and the gained energy savings. As more efficient renovation measures are more expensive investment costs and interest charges will be higher. The change of the heat source seems to have a significant impact on both the cost and the PE of the renovation packages. Combining insulation measures with different heat sources results in significant difference. Gustafsson [14] and Verbeeck and Hens [13] have additionally shown the importance of the heating system. The differences are relatively small between WPB and GB heating. DH and AWHP show the highest ΔNPV values because of the high investment costs for the equipment. To reach the minimum requirement of 180 kW h/(m^2 a), the lowest ΔNPV was found in the case of WPB and GB when the investment and the running costs do not exceed the running costs of the reference building. In the cases of the DH and AWHP, the cost-efficiency is exceeded. If the target is not set to meet the minimum requirement, the ΔNPV line stays well below zero giving the opportunity to choose renovation packages depending on the desired PE with different heat sources and insulation measures.

There can be different renovation strategies to improve the energy efficiency of existing buildings: with BAU, the −40% level was achieved without changing the heating system; with HER and NPV, the −45% level was reached when the appearance was affected the least. To reach the EPV level set in regulations in all the cases, the stove heating system has to be replaced by a new more efficient heat source and heating system. With BAU, the ventilation air change rate being 0.35 l/(s m^2) and no heat recovery taken into account, the heat loss through air change has to be compensated for by adding a thicker layer of wall insulation to reach the PE level set in regulations. If the ventilation air change rate is increased, the PE level set in the regulations is not reached. In the HER and NPV cases, the ventilation air change rate was 0.42 l/(s m^2) and the ventilation system was with heat recovery. If heat recovery is taken into account, it leaves the possibility to use a thinner layer of thermal insulation in the external wall. Ventilation heat recovery has to be used if the characteristics and appearance of the building are taken into account. The ΔNPV values show that it is economically viable only to change the heat source and increase the efficiency of the heating system or implement the renovation package with the maximum insulation measures allowed. The risk of not using the optimal solution and the extra costs associated with the change of the heat source before the end of its lifetime exist. A whole simultaneous building retrofit is preferred, but often the large investments for the retrofit works can create obstacles. Therefore, the order of the renovation methods is important.

For the owners, the initial high cost of the major insulation measures can be a significant concern. Additionally, the costs of technical and bureaucratic issues can be obstacles to more energy efficient buildings, especially in the case of historic buildings. A conflict between the economically viable solutions and the sustainable conservation issues can emerge. The energy retrofit can be done in combination with renovation, replacement or other improvements to reduce the financing issue. In the near future there will be a serious need for extensive construction work to preserve these historic wooden apartment buildings [29]. Improving the energy efficiency of building components at the time of retrofit and potential added value to the property [43] can help to overcome the financing barriers. The willingness to make buildings more energy efficient can be increased if the minimum requirement of PE for the historic buildings and existing buildings subject to major renovation are considered separately. By reducing the PE, a wider range of renovation packages becomes available. The ΔNPV value curves indicate that the cost optimal PE of 250 kW h/(m^2 a) could be considered in the historic wooden apartment buildings.

5. Conclusions

The study is limited to the historic wooden apartment buildings in Estonia. We analyzed the energy consumption of 29 wooden apartment buildings. Their primary energy consumption was higher than the limit in minimum requirements for the buildings subject to major renovation. Four reference buildings were chosen from the studied buildings for simulations to compare the effect of possible renovation measures. It was found that the minimum requirement of 180 kW h/(m^2 a) is achievable if the new heating system is combined with the attic floor insulation, cellar ceiling insulation and with new windows or wall insulation. A maximum of 63% reduction was achieved in the case of the pellet boiler heat source with a heat recovery ventilation system, and with all the maximal insulation measures considered.

The investment costs of renovation measures and energy costs were used to compare the effectiveness of different renovation packages. The results of the economic assessment showed that higher energy savings from different insulation measures combined ,without considering the building service systems do not increase the cost-effectiveness. Combining insulation measures with building service systems broadens the possibilities and higher energy savings can be achieved in an economically viable way. The results of the economic assessment indicate that the cost optimal PE of 250 kW h/(m^2 a) could be achieved in historic wooden apartment buildings.

Considering the construction work needed to preserve the buildings and helping owners to overcome the technical and economic barriers can result in more active retrofitting, and as a result in higher energy savings.

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PAPER II

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BUILDING
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Indoor climate conditions and hygrothermal loads in historic wooden apartment buildings in cold climates

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Abstract. To design and assess indoor climate, thermal comfort, and the hygrothermal performance of a historic building it is essential to obtain data on the indoor temperature and humidity conditions. This paper analyses indoor climate conditions in historic wooden apartment buildings in Estonia and presents an applicable hygrothermal load model for designers. The average indoor temperature of 41 apartments in historic wooden apartment buildings was 21.0 °C in winter and 24.5 °C in summer. Using the indoor climate category III of the standard EN 15251, it was found that the temperature was outside the target values in 83% of the apartments in winter and in 25% in summer. Throughout the year, the indoor temperature was below the target values during 20% of the time while in winter it was above the target values during 4% of the time. Variations in indoor temperature reflect occupants' main complaints about unstable temperature and cold floors during the winter period. The daily average moisture excess was 3.3 g/m^3 during the cold period and 0.6 g/m^3 during the warm period at the average air change rate of 0.56 h^{-1} and 0.79 h^{-1}, respectively. Moisture generation indoors was 60 g/h at the average living density of 26 m^2/person in the historic wooden apartment buildings. For stochastic analyses in historic wooden buildings, we developed an indoor hygrothermal load model that is in good agreement with measured results.

Key words: building physics, hygrothermal load, indoor climate, moisture excess, historic wooden building.

INTRODUCTION

In the course of time, the use of historic buildings has changed. Today people have different requirements for thermal comfort, energy performance, and functionality of the buildings. Vast quantities of energy are consumed for heating and cooling to ensure standards of thermal comfort acceptable in today's terms (Chappells and Shove, 2005). As the energy prices are rising fast, living in low energy efficiency historic buildings can raise the costs of keeping the thermal comfort at an acceptable level (Arumägi and Kalamees, 2014). The cost of living has increased, and for many people the standard of living is falling in line with a corresponding increase in fuel poverty (Nicol and Stevenson, 2013).

Building users consider thermal comfort to be the most important parameter influencing their overall satisfaction with indoor environmental quality, and thermal comfort is influenced by the type of building, outdoor climate, and season (Frontczak and Wargocki, 2011). Oreszczyn et al. (2006) quantified the variations in the indoor temperatures in the heating season and explained these by the characteristics of the dwelling and the household and by energy efficiency improvements. Some very low indoor temperatures were indicated, which reflect a combination of the efficiency of the heating system and insulation, the capacity (maximum rate of energy consumption) of the heating system, and personal choice/behaviours. In their review

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of domestic dwelling temperatures during the heating season, Hunt and Gidman (1982) conclude that the age and the type of the heating system have a strong influence on the temperature model.

Indoor temperature is considered as the most important factor to assess the thermal comfort in a building. In addition, indoor humidity is necessary in the assessment of the building performance. Data on indoor air humidity in buildings are needed for many purposes. Indoor air humidity loads have been investigated in different field studies. Kalamees et al. (2006) presented a thorough literature review about the moisture excess in dwellings, showing a large variance in the results and pointing out short measurement periods. Geving and Holme (2012) studied the mean and diurnal indoor air humidity loads in residential buildings and concluded that measurements of the indoor air humidity should be made on a long-term basis.

A frequent moisture problem in cold climates is related to high indoor humidity levels in winter. In cold climates, excessive indoor humidity can lead to moisture accumulation with its many unwanted consequences, including microbial growth, poor indoor air quality, and potential health problems for the occupants (Bornehag et al., 2004; Glass and TenWolde, 2009). The most often occurring spores are usually also the spores with the highest health risk. Depending on the indoor climate conditions and human response to the irritants, the number of spores in the indoor air need not be very high to cause health problems.

Asikainen et al. (2013) pointed out that large numbers of residences in European countries have mean ventilation rates below the requirements of the national building regulations or codes. The residents play an important role in the ventilation level in their own homes. Surveys of occupants showed that people generally think that ventilation is important, but their understanding of the ventilation systems in their homes is inadequate. The chain of activities from design through execution to use and maintenance, especially those of mechanical ventilation systems, shows weak links. Higher set points required to achieve adequate ventilation are seldom used due to the noisy fans. Thus, poor use and lack of occupants' knowledge seem to be main problems in the under-ventilated homes (Dimitroulopoulou, 2012).

Reasons for low temperatures and air change rates in the historic buildings often lie in the old building systems that have not been upgraded. A relation between the occurrence of mould growth and indoor air humidity levels was shown by Oreszczyn et al. (2006). High levels of humidity and some surface and interstitial condensation may be sufficient for mould growth; these may occur due to water damage from leaks, flooding, and groundwater intrusion or due to construction faults, including inadequate insulation, in combination with poor ventilation (WHO, 2009). Su (2002) found that visible mould growth on indoor surfaces is a relatively common problem in aged residential buildings that lack sufficient insulation. By improving the building envelope with additional insulation, it is possible to increase thermal comfort, save energy, and lower the risk of mould growth and condensation on indoor surfaces. For reasons of preserving architectural appearance, facade changes of historic buildings are often prohibited. Internal insulation is a possible solution when a high value architectural appearance must be preserved. However, internal thermal insulation may cause hygrothermal risks; thus, special requirements are set for the renovation solutions. In addition to the material properties, the boundary conditions are also important (Zhao et al., 2011). To achieve moisture-safe buildings, data concerning deterministic and stochastic indoor humidity loads for the design and risk analysis must be accurate (Hens, 1999; Mjörnell et al., 2012).

Indoor temperatures vary by the building type and the construction. Field data about the indoor climate conditions in historic wooden apartment buildings are scarce. Unless measured conditions are available, realistic estimates of the boundary conditions are needed (Glass and TenWolde, 2009). Indoor temperature and humidity conditions are essential data for the assessment of indoor climate and thermal comfort as well as the hygrothermal performance of the historic buildings.

This paper focuses on indoor climate conditions and problems related to the indoor climate in historic wooden apartment buildings. Based on the long-term indoor temperature and relative humidity measurements, the indoor hygrothermal conditions in the current situation are analysed. In addition, the indoor air quality is assessed based on the CO_2 measurements and air sampling. To find relations between the measured indoor climate parameters and the inhabitants' complaints, the occupants' responses to a questionnaire are analysed. User satisfaction to the living conditions based on this questionnaire is presented. Finally, a hygrothermal load model applicable for stochastic hygrothermal performance analysis is suggested.

METHODS

Studied buildings

The study concentrates on historic wooden apartment buildings (Fig. 1) built before 1940 in Estonia. The average age of the buildings is 98 years. Altogether 29 buildings and 41 apartments were investigated. The focus was on indoor climate studies, measurements, and a survey of the building envelope properties.

The average apartment area is 59.3 m^2 and the average number of inhabitants is 2.3. Typical wall constructions of the buildings consist of horizontal or

Fig. 1. Street view of two studied wooden apartment buildings in Tallinn.

vertical logs with an external wooden cladding or render. The external walls contain no additional thermal insulation. The typical wall thickness is between 150 and 200 mm. Typical wooden-framed windows consist of two panes. Original heating systems are wood burning stoves, and ventilation is by the natural passive stack.

In general, the discharge takes place through the chimneys and the compensation through the building body, which means that the air change rate in the studied buildings depends on their air tightness. The reason is in the absence of fresh air valves in the majority of cases. The average air leakage rate at 50 Pa (q_{50}) pressure difference was 10.5 m^3/(h·m^2) (varied from 4 to 18 m^3/(h·m^2)) and the air change rate (n_{50}) was 12.5 h^{-1} (varied from 5 to 24 h^{-1}).

Measurements

Technical conditions were inspected visually for each building (Klõšeiko et al., 2011). In addition, a questionnaire was conducted for each building to obtain information about the occupants' habits, typical complaints, and symptoms related to indoor air quality.

Temperature and relative humidity (RH) were measured continuously with data loggers (measurement range –20 to +70 °C, 5–95% RH, accuracy respectively ±0.35 °C and ±2.5% RH). Temperature and RH inside the bedroom and outside the building were recorded at one-hour intervals. The indoor loggers were located on separating walls in the master bedroom or in the living room and in reference measurement points. Loggers to measure outdoor temperature were placed on the north side of the building, protected from direct solar radiation.

The moisture excess $\Delta\nu$ (g/m^3) (the difference between the indoor and the outdoor air water vapour content) was calculated on the basis of the indoor and outdoor temperature and RH measurements:

$$\Delta\nu = \nu_\mathrm{i} - \nu_\mathrm{e} = \frac{G}{q_\mathrm{v}} \ \ (\mathrm{g/m^3}), \qquad (1)$$

where ν_i is the indoor air water content, g/m^3; ν_e is the outdoor air water content, g/m^3; G is the moisture production indoors, g/h; and q_v is the ventilation air flow, m^3/h.

To analyse the dependence of the moisture excess on the outdoor climate and to determine the critical moisture excess values, the data were sorted according to the outdoor air temperature, using a 1 °C step of the outdoor temperature. The sorted values were used to calculate average, maximum, minimum, and 10% critical levels.

The levels of CO_2 in the bedrooms were measured during the winter and summer periods to assess the air change in the apartments. The CO_2 levels were measured at 10-min intervals during 2 to 3 weeks using CO_2 monitors with data loggers (measurement range 0–10 000 ppm, with an accuracy of ±5% of the reading or 50 ppm).

The air change calculations were based on the measurements of indoor CO_2 levels and estimated CO_2 emissions from the inhabitants (Guo and Lewis, 2007):

$$C_{\mathrm{i},t} = C_\mathrm{e} + \frac{E}{R_\mathrm{a}} - \left(C_\mathrm{e} + \frac{E}{R_\mathrm{a}} - C_{\mathrm{i},0}\right)\cdot e^{-\frac{R_\mathrm{a}}{V}\cdot t}, \qquad (2)$$

where $C_{\mathrm{i},t}$ is the CO_2 concentration at time t (ppm); C_e is the CO_2 concentration of the outdoor air (ppm); E is the CO_2 generation rate (13 L/(h·pers); R_a is the ventilation and infiltration airflow (m^3/s); $C_{\mathrm{i},0}$ is the CO_2 concentration at the beginning of the time period (ppm); V is the effective volume of enclosure (m^3); t is the time (s), and e is Euler's number. We used the measurement results from the night-time (23:00–7:00) in our calculations.

Air sampling was used to assess the quality of the indoor air in the buildings. A Biotest HYCON Air sampler RCS was used to take the air samples. For sample collection Y and F sampling stripes and 4-min sample times were used. The incubation time was 8 days at the temperature of 21 °C for later analysis. No mould species were detected in the incubated air samples. In this study the samples were collected during winter months (January and February) when the outdoor temperature prevails below 0 °C and the concentration of the spores in the outdoor air is very low. Our results are expressed as colony forming units (cfu) per volume of air (for air samples).

The tape sampling technique was used to identify mould taxa in the buildings where discoloration of surfaces or mould growth was detected during visual inspection. Samples were taken in kitchens, bedrooms, or washing rooms or if mould growth was detected, in living rooms. Adhesive tape lift samples were collected using 3M Crystal Clear Tape.

Assessment

Target values from the indoor climate category III (CR 1752, 1999; EN 15251, 2007) were used to assess indoor thermal conditions: 18–25 °C during winter months and 22–27 °C during summer months. Indoor climate category III represents an acceptable moderate level of expectation used for existing buildings. In the thermal evaluation, an hourly criterion is used, based on the calculation of the percentage of time when the criteria are met or are outside a specified range.

The ventilation rates required are specified as an air change per hour for each room, and/or outside air supply, and/or required exhaust rates (bathroom, toilets, and kitchens) or given as an overall required air-change rate (EN 15251, 2007). According to the indoor climate category III, the required overall air-change rate should be 0.5 h^{-1} or 4 L/s per person or 0.6 L/s per m^2 of the bedroom.

Air sampling results are expressed as colony-forming units (cfu) per volume of air (for air samples). Singh et al. (2010) presented the levels recommended in Great Britain. Husman et al. (2002) provided the limits for the quantity of fungal spores in the indoor air used in Finland. The levels in these two studies differ by an order of magnitude. As the relation between dampness, microbial exposure, and health effects cannot be quantified precisely, no quantitative health-based guideline values or thresholds can be recommended for acceptable levels of contamination with microorganisms (WHO, 2009). As no limits have been set in Estonia, the Finnish standard was used in our comparison because of similarities in Estonian and Finnish climates. The quantity of fungal spores in the indoor air was compared with the hazard classes presented in the WHO (2009) guidelines.

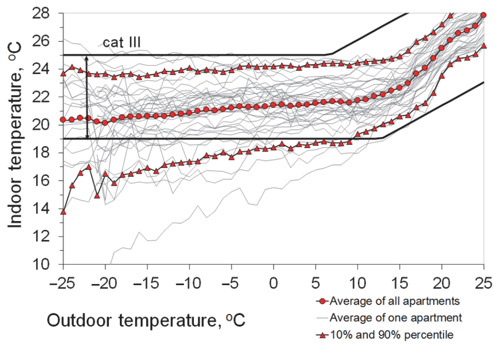
RESULTS

Indoor hygrothermal conditions

To determine the temperature and humidity loads, the dependence of the indoor temperature and moisture excess on the outdoor temperature was analysed (Fig. 2). The average indoor temperature during the winter period was 21.0 °C (SD 2.3 °C, min 13.3 °C, and max 24.8 °C) and during the summer period 24.5 °C (SD 1.1 °C, min 22.7 °C, and max 26.7 °C). During winter the indoor temperature was outside the category III (EN 15251, 2007) target values in 83% of the apartments and during summer in 25% of the apartments. Throughout the year the indoor temperature was below the target values on average for 1731 h in winter and for 20 h in summer and above the target values on average for 345 h in winter and for 49 h in summer.

The diurnal moisture excess during the cold period ($t_e \leq +5$ °C) was 3.3 g/m^3 (SD 1.1 g/m^3) and during the warm period ($t_e \geq 15$ °C) it was 0.6 g/m^3 (SD 0.7 g/m^3).

(a)



(b)

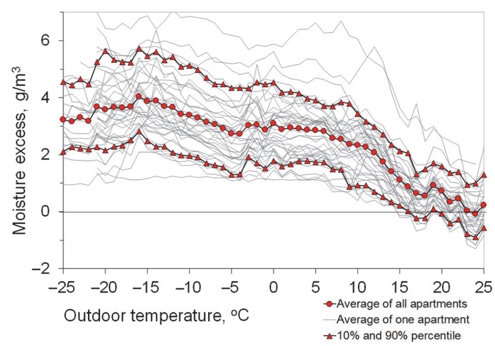


Fig. 2. Dependenc of indoor temperature (a) and moisture excess (b) measurement results on the outdoor temperature (Sanders, 1996).

The average of 90% percentile from the diurnal moisture excess during the cold period was 5.1 g/m^3 and during the remaining time 3.0 g/m^3. Weekly average moisture excess values were 3.0 g/m^3 (SD 1.1 g/m^3) and 0.7 g/m^3 (SD 0.7 g/m^3), average of 90% percentile 4.3 g/m^3 and 1.9 g/m^3, respectively.

A temperature and humidity load model for hygrothermal design can be derived from the measurement results. The indoor temperature and moisture load design curves for the historic wooden apartment buildings are presented in Fig. 3 (described by Eqs 3 to 6). Indoor temperatures show a turning point at the outdoor temperature of +15 °C. The average indoor temperature curve rises from 20 °C to 22 °C during the heating season when outdoor temperatures range from –25 °C to +15 °C. After the outdoor temperature level of +15 °C, the incline of the curve is steeper and the indoor temperature rises from 22 °C up to 28 °C. The moisture excess curve shows turning points at the outdoor temperatures 5 °C and 20 °C. During the cold period ($t_e \leq +5$ °C), the average moisture excess curve stays at the level of 3.3 g/m^3 and during the warmer period ($t_e \geq +20$ °C) at the level of 0.6 g/m^3. The moisture excess curve shows a linear change between the turning points at the outdoor temperatures 5 °C and 20 °C.

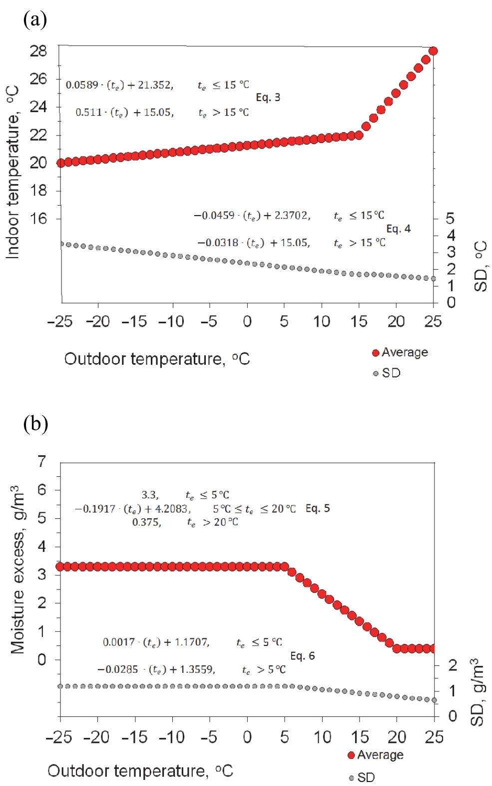


Fig. 3. Indoor temperature (a) and moisture load design curves (b) for historic wooden apartment buildings.

The dependence of the standard deviation on the outdoor temperatures describes variations in the average values. In stochastic analyses, the distribution of values is needed. The difference demonstrates possible variations in occupants' habits on the one hand and the differences in the heating capacities and thermal resistance on the other hand. The standard deviation curve of indoor temperature, on the contrary, remains opposite in relation to the indoor temperature. The standard deviation shows a linear correlation on the outdoor temperature, the curve declines from the value 3.5 at –25 °C to the value 1.5 at +25 °C. Standard deviations of moisture excess show a linear correlation on the outdoor temperature; the curve declines from the value 1.2 at the outdoor temperatures –25 °C to +5 °C and declines to the value 1.5 at +25 °C (see Fig. 3).

The indoor relative humidity (RH) was calculated with the indoor temperature and moisture excess models to test the conformity of indoor RH conditions to those in reality. The indoor RH was calculated for the number of cases equal to the number of apartments where the indoor climate was measured. A model using random sampling was applied to calculate RH. First, knowing the outdoor temperature (t_e), the average indoor temperature (t_i), moisture excess (Δv), and standard deviations (σ_{ti}, $\sigma_{\Delta v}$) were calculated by Eqs 3–6 in Fig. 3. As the next step, assuming normal distribution and using the average values and standard deviations, random sampling was done. Knowing the outdoor RH and temperature, the indoor air vapour content was calculated using Eq. 1. The indoor RH was calculated using the indoor air vapour content and saturation content at the corresponding indoor temperature. As the last step, the calculated values of indoor RH and indoor temperature were averaged using a 24-h running average.

There was good agreement between the measured and the calculated indoor RH values (Fig. 4a). The cumulative distributions of the measured and the calculated results from five outdoor temperatures (–25 °C, –10 °C, 0 °C, +5 °C, and +15 °C) were compared. Even at good agreement between the measured and calculated RH values, the calculated results show slightly larger aberrancy at higher outdoor temperatures (Fig. 4b). Generally, the calculated RH levels are higher than the measured RH levels at an equal number of calculated and measured values.

Another possibility of presenting indoor humidity loads is through the indoor moisture production and the ventilation rate (Eq. 1). During winter the average ventilation airflow in the bedrooms was 0.43 L/(s·m^2) (varied between 0.1 and 1.5 L/(s·m^2)), and the average

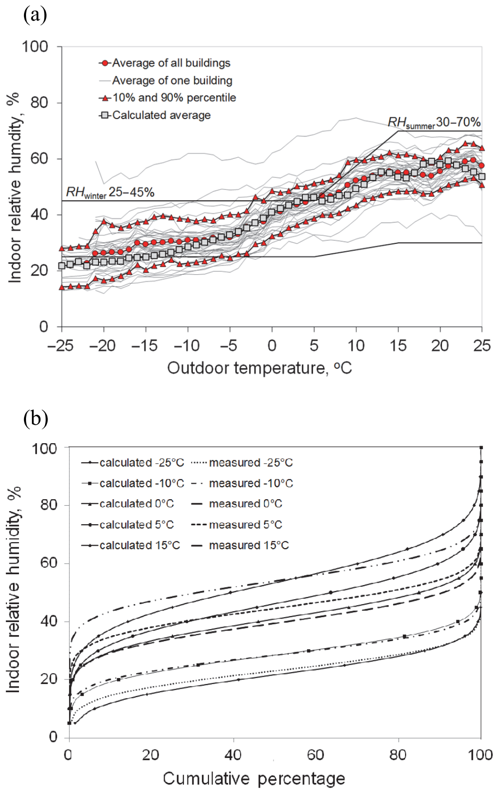


Fig. 4. Indoor air relative humidity measurement results (a) and comparison of measured and calculated values (b) at different outdoor temperatures.

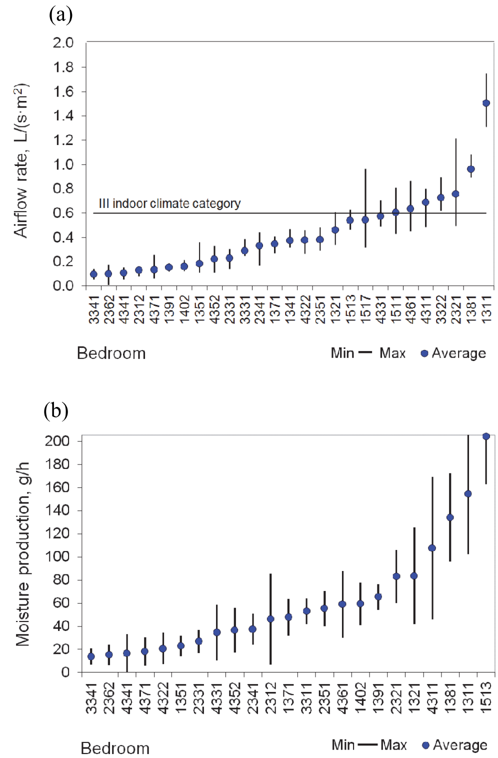


Fig. 5. Airflow rate (a) and moisture production (b) in bedrooms during winter period.

air-change rate in the bedrooms was 0.56 h^{-1} (varied between 0.1 and 2.0 h^{-1}) (Fig. 5). During summer the average air-change rate in the bedrooms was 0.79 h^{-1} (varied between 0.1 and 2.2 h^{-1}). The average air-change rate satisfies the target value for indoor climate category III. The minimum required air change is met in 44% of the bedrooms. However, in terms of airflow per floor area, only 26% of the bedrooms complied with the target value of climate category III.

The average moisture production in the bedrooms during night was 60 g/h (variation between 14 and 200 g/h). The calculated moisture production shows mainly moisture from inhabitants and common household activities as the ventilation airflow rate and moisture excess values are measured during the night-time. These values include also moisture transport between the room air and the building fabric. The presented moisture production values can be used as input values for the indoor climate of a whole building, and energy simulation programs targeted to moisture transfer between the room air and the building fabric are neglected. When advanced numerical hygrothermal tools are used in the simulation programs covering the whole building and the moisture transfer between the room air and the building fabric is taken into account, the corresponding moisture production value should be larger than the measured average production during night in the bedrooms. Based on moisture buffering studies (Svennberg et al., 2004; Rode and Grau, 2008), moisture buffering mainly influences daily variations in the range from 10% to 40%, depending on the furnishing and building fabric.

Indoor air quality

Indoor CO_2 concentrations were used as one of the indicators of indoor air quality because occupants are the main pollution source in dwellings. During our measurements, the peak values varied between 1287 ppm and 3999 ppm in the wintertime. During the winter period, the average value of all the bedrooms (occupied) was 1084 ppm (varied between 537 and

1972 ppm) in the night-time. During the summer period, the average value of all the bedrooms was 1062 ppm (varied between 614 and 1565 ppm). The measured CO_2 concentrations were above 1000 ppm for 51% of the measurement time in the winter period and for 45% of the measurement time in the summer period. The measured CO_2 concentrations were above 1500 ppm for 18% of the measurement time both in winter and summer periods.

Another indicator of indoor air quality studied was occurrence of fungal spores in tape lift samples. No fungal spores were found in half of the samples (Table 1). The largest numbers of spores found in the indoor air belonged to the genera *Cladosporium* and *Phoma* found in 13% and 10% of the samples, respectively (Table 1). Spores of other identified genera of fungi occurred in 2–3% of the samples. The spores most frequently found in apartments are the spores with the highest health risk (Singh, 2000). Moreover, the number of spores in the indoor air need not be very high to cause health problems.

No relevant correlation (low R^2) was found between the numbers of spores in the indoor air and the average indoor temperature in the apartments. Indoor RH (moisture excess, moisture production) and air change rate (ventilation, air tightness) in the apartments showed a higher correlation with mould growth: the higher were the moisture excess and the RH, the higher was the number of spores in the indoor air. In case the average moisture excess was over 6 g/m^3 and the RH was over 60%, the numbers of spores in the indoor air were higher than the acceptable level 500 cfu/m^3 (Fig. 6).

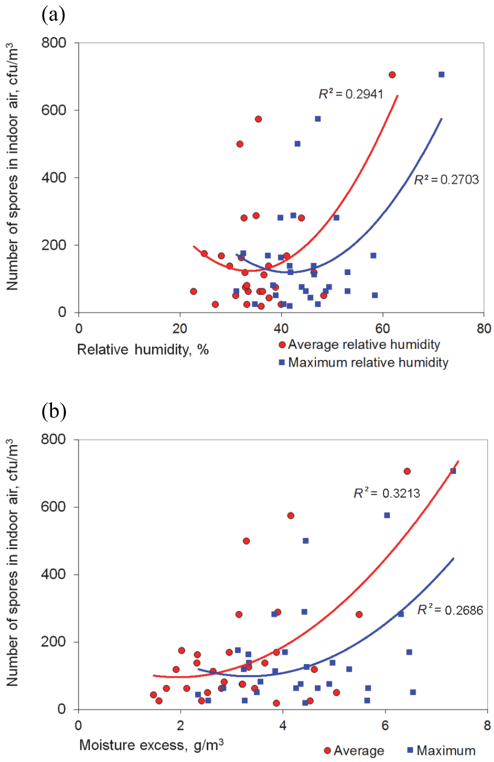


Fig. 6. Dependence of the number of spores in the indoor air on the indoor air relative humidity (a) and moisture excess (b).

User satisfaction

A questionnaire was conducted in each building to survey occupants' habits, typical complaints, and symptoms related to the indoor air quality. To ensure reasonable data collection about the inhabitants' opinions in a simple context, the questions concerned seriousness and frequency of the problems. Considering the cold outdoor climate, most questions were targeted to the indoor conditions during the heating period when the heating and ventilation systems are of critical importance. The main problems indicated by inhabitants were unstable temperature, cold floors, and stuffy air during the winter period (Fig. 7).

The occupants' responses were used to find relations between the measured indoor climate parameters and the inhabitants' complaints. Despite the fact that the average temperature in most of the buildings was on an acceptable level, inhabitants complained about the unstable indoor temperature. Indeed, the diurnal temperature variations were great and the indoor temperature was prevailingly outside the target levels. Inhabitants complained about the unstable temperature during the winter-time if the average daily temperature variation was 3.8 °C; which is 1 °C higher than in the buildings with no complaints ($p = 0.045$). Besides, periods with the indoor temperature outside the target levels were 26% longer in buildings with complaints. The

Table 1. Occurrence of fungal spores of different genera in tape lift samples

Find	% of occurrence
Chaetomium	2
Cladorrhinum	2
Cladosporium	13
Echinobotryum	2
Epicoccum	2
Exophiala	3
Phoma	10
Ulocladium	3
Unidentified spores	10
Unidentified mycelium	3
No spores (soot, dust)	50
Total	100

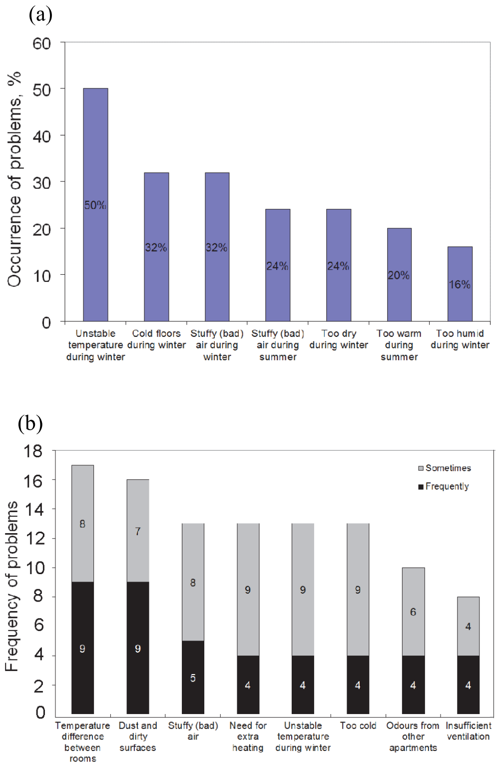


Fig. 7. Occurrence (a) and frequency (b) of the problems based on the questionnaire.

survey showed that complaints about the indoor temperature concerned 42% and absence of complaints 16% of the time, which is not in compliance with the indoor climate category III.

Problems with cold floors during winter ($p = 0.019$) occurred in apartments with unstable temperature. The reason probably lies in the infiltration and low thermal resistance of the constructions or in an insufficient power of the heating system. Buildings with larger temperature variations and cold floors during winter were much leakier and had a higher air-change rate n_{50} ($p = 0.036$) and larger energy consumption ($p = 0.047$) than buildings with no occupants' complaints.

DISCUSSION

International standards like ISO 7730 (2005) and ASHRAE 55 (2013) have derived substantially from the studies of thermal comfort, to guide the built environment professions to design and maintain comfortable indoor thermal environments (de Dear, 2004), but in reality the indoor climate conditions may differ considerably in historic buildings.

Our results show that while the average indoor temperature during the winter period was 21.0 °C, large variations occurred in indoor temperatures. Because of large heat losses and insufficient heating capacities, the measured indoor temperatures were lower during the heating period. At lower outdoor temperatures, the scattering in the measured results showed almost two times larger deviation than at warmer outdoor temperatures. Large variations in the indoor temperature can be explained by the characteristics of a particular building, such as low thermal transmittance of building constructions, large air leakages, and insufficient power of heating systems, as well as by the behaviour of the occupants (Becker and Paciuk, 2009).

For hygrothermal dimensioning of the building envelopes, sufficiently critical humidity loads should be considered. Sanders (1996) recommended the use of 10% percentile as the critical level. This means that hygrothermal loads higher than their normative value should not appear in more than 10% of the cases. Another approach would be a stochastic analysis taking into account more realistic conditions. This paper presents the average values with distributions.

The hygrothermal design curve for the buildings with low occupancy (average 43 m^2/person) was presented by Kalamees et al. (2006), showing the maximum moisture excess 4 g/m^3 during the cold period ($t_e \leq +5$ °C), 1.5 g/m^3 during the warm period ($t_e \geq 15$ °C), and a linear change between the cold and the warm period. Geving and Holme (2012) proposed design curves that depend on the occupancy and the moisture production as 'low' (low occupancy <0.02 person/m^2), 'medium' (medium/high occupancy >0.02 person/m^2), and 'high' (bathrooms and laundry rooms). Moisture excess values to design curves during cold periods ($t_e \leq +5$ °C) are 2.5 g/m^3 (low), 4 g/m^3 (medium), and 6 g/m^3 (high). Moisture excess values to design curves during warm periods ($t_e \geq 15$ °C) are 0.5 g/m^3 (low), 1.5 g/m^3 (medium), and 3 g/m^3 (high). Between the cold and the warm period there is a linear change. In this study the average occupant density was 26 m^2 per person (0.04 person/m^2). The level of the moisture excess model curve derived from our measurement results appears to be the same as the 10% critical level in other studies. The moisture excess level is higher than in (Kalamees et al., 2006) and (Geving and Holme, 2012), which correlates with higher occupant density and lower ventilation air-change rate.

Metabolic CO_2 can be used as an indoor air quality indicator. Indoor CO_2 concentrations above 1000 ppm are generally regarded as an indicator of inadequate ventilation. In Nordic residential buildings, ventilation rates below half an air change per hour are considered too low, which may lead to high concentrations of pollutants and cause health problems (Wargocki et al., 2002; Sundell et al., 2011). Indoor humidity is influenced by the ventilation rate. Ventilation usually reduces indoor moisture levels. Older buildings and the use of natural ventilation are associated with increased frequency of dampness indicators as well as with increased frequency of complaints on bad indoor air quality (Hägerhed et al., 2002).

In the studied buildings, the frequency of overall appearance of spores in the indoor air is distributed unevenly. The largest numbers of spores found in the indoor air of the wooden apartment buildings are also the spores with the highest health risk (Singh, 2000). Depending on the inhabitants' response, the number of spores in the indoor air need not be very high to cause health problems. The number of spores in the indoor air of more than 50% of the studied wooden apartment buildings was lower than 150 cfu/m^3 and was smaller than the numbers of different fungal genera in the indoor air in the brick and concrete-element apartment buildings (Kalamees, 2011). According to our results, ventilation in wooden apartment buildings is inadequate as the presented air-change values include also air change between rooms when the communicating door is open. In spite of the high living density and poor thermal transmittance of the buildings, air samples with the number of spores lower than 150 cfu/m^3 were found in more than half the buildings. The result seems good and it is in correlation with the number of air samples with no spores. The main reason is that there are fewer critical thermal bridges in wooden apartment buildings than, for example, in brick and prefabricated reinforced concrete large-panel element apartment buildings (Ilomets et al., 2014).

Overall, the majority of the occupants in the historic wooden buildings did not complain about the indoor climate conditions. In our study, most of the complaints concerned unstable temperature and low temperature of the floor during the winter period rather than the air quality or noise problems. The reason is that the occupants rank thermal comfort as more important than good air quality and acoustic comfort (Frontczak and Wargocki, 2011). Another reason may be that human adaptation is more active in naturally ventilated buildings and that the zone of equal thermal sensation for naturally ventilated building occupants is generally broader than for those in heated and ventilated and air-conditioned buildings. In naturally ventilated buildings, the thresholds are broad due to the occupant-adaptive behaviour in the presence of outdoor climate (Zhang et al., 2011). In most of the studied buildings, inhabitants have control over the environment, and this has been seen as an indoor environment improvement factor (Frontczak and Wargocki, 2011). Because of the peculiarities of historic buildings, their occupants tend to tolerate deficiencies characteristic of apartments in such buildings to a considerably greater extent than those of more recent buildings.

CONCLUSIONS

The focus of this study was on the indoor climate conditions of historic wooden apartment buildings. Altgether 29 buildings and 41 apartments were investigated.

The measured indoor temperatures revealed a linear dependence on the outdoor temperatures, showing a twice as large deviation at lower outdoor temperatures as at higher outdoor temperatures. Indoor temperature was outside the category III target values in 83% of the apartments in winter and in 25% of the apartments in summer. Indoor temperature variations reflect also the complaints concerning the unstable temperature and cold floors during the winter period.

The indoor climate conditions differ from those in more recently built apartment buildings and it is necessary to improve their indoor thermal comfort. Even though most of the time the thermal comfort was outside the acceptable moderate level of expectations, the building occupants showed overall satisfaction with the living environment in historic wooden apartment buildings.

Typically, to assess the hygrothermal performance and the moisture risks of the constructions the deterministic approach is used in the design process. The reliability can be defined as the probability for a solution to function without failure during a given period of time. The reliability concept requires the assessment of probabilities, calling for the application of probabilistic methodologies rather than deterministic techniques (Janssen, 2013). For the hygrothermal analysis of the building envelope, the modelling curves of the indoor temperature and moisture excess were derived from the measurement results. The curves of the indoor temperature and moisture excess reveal their dependence on the average value and standard deviation of the outdoor temperature. The presented curves can be used for dynamic simulations of hygrothermal performance.

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Sisekliimatingimused ja niiskuskoormused ajaloolistes puitkorterelamutes

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Et projekteerida ja hinnata sisekliimat, soojuslikku mugavust või niiskustehnilist toimivust ajaloolises hoones, on oluline teada ruumide sisetemperatuuri ning suhtelise niiskuse tingimusi hoones. Hindamaks uuritavate hoonete sisekliimat, tehti pikaajalised sisetemperatuuri, suhtelise niiskuse ja CO_2 mõõtmised 29 ajaloolise puitkorterelamu 41 korteris. Lisaks sisekliimatingimuste analüüsile on esitatud uuritud hoonetüübile rakendatav niiskuskoormuste mudel. Analüüsitud 41 korteri mõõtmisandmete põhjal oli korterite keskmine sisetemperatuur talvel 21,0 °C ja suvel 24,5 °C. Sisekliima mõõtmised näitasid, et korterite sisetemperatuur oli väljaspool sisekliima III klassi piirsuurusi talvel 83% ja suvel 25% ajast. Sisetemperatuuri kõikumised peegeldavad hästi elanike kaebusi muutuva sisetemperatuuri ja külmade põrandate osas talvisel ajal. Vaadates talvist perioodi, oli sisetemperatuur madalam alumisest piirsuurusest 20% ajast ja kõrgem ülemisest piirsuurusest 4% ajast. Välis- ja sisekliima mõõtmiste põhjal arvutati ruumide niiskuslisa. Külmal perioodil oli päevane keskmine niiskuslisa 3,3 g/m^3 ja soojal perioodil 0,6 g/m^3. Ruumides tehtud CO_2 mõõtmiste põhjal arvutatud keskmine õhuvahetus oli talvel 0,56 h^{-1} ja suvel 0,79 h^{-1}. Arvestades arvutuslikku õhuvahetust ja keskmist asustustihedust 26 m^2 inimese kohta, oli korterites hinnanguline keskmine niiskustoodang 60 g/h. Ajalooliste puitkorterelamute sisekliimatingimused erinevad oluliselt tänapäevaste korterelamute sisekliimast, mis näitab tehnosüsteemide ja hoone välispiirete renoveerimise vajadust.

Mõõtmistulemuste põhjal koostati sisetemperatuuri ja niiskuslisa modelleerimise mudel, mis võimaldab stohhastilist analüüsi. Sisetemperatuuri ja niiskuslisa suurused on kirjeldatud sõltuvuses välistemperatuurist läbi keskmiste suuruste ning tõenäosuslike hajuvustega. Koostatud mudelit saab kasutada hoonepiirete niiskustehnilise toimivuse analüüsiks.

PAPER III

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Reliability of interior thermal insulation as a retrofit measure in historic wooden apartment buildings in cold climate.

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Abstract

The performance of the interior insulation as a retrofit measure in historic wooden building was analysed. The designers' view is that an interior insulation of 50mm mineral wool with vapour barrier is a safe solution. Probability of failure using mold growth risk as an indicator was calculated using stochastic method. Sensitivity analyses revealed that the existence of the vapour barrier is most influential. In addition, the insulation material layer is of critical significance. Of the boundary conditions the moisture excess has a higher effect than indoor temperature. The calculated probabilities showed high risk. Therefore, the considered insulation solution is an unreliable retrofit measure.

Keywords: hygrothermal performance; interior insulation; retrofit; historic building; moisture safety.

1. Introduction

There is a need to improve thermal comfort and energy performance of the historic buildings to meet modern requirements. Interior insulation is a possible solution when the architectural appearance is of high value and must be preserved. However, internal insulation may cause hygrothermal risk, therefore special requirements for the renovation solutions are set. To achieve a moisture safe renovation solution, careful design and risk analysis are needed.

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Typically, to assess the hygrothermal performance and the moisture risks of the constructions the deterministic approach is used in the design process. The reliability can be defined as the probability for a solution to function without failure during a given interval of time. The reliability concept fundamentally requires the assessment of probabilities, calling for the application of probabilistic methodologies rather than deterministic techniques [1]. The different parameters influencing the hygrothermal performance of the retrofit measure have a stochastic nature. A stochastic method enables variations in material properties, climatic conditions, boundary conditions and differences in wall assemblies to be considered. The analyses can be carried out through testing the influence of a single input parameter to testing all input parameters.

In several studies stochastic approach have been applied in the analysis of hygrothermal performance. The influence of material properties is reported in [2, 3, 4], the influence of one part of the wall assembly in [5], the performance assessment of interior insulation in [6], the performance of the building envelope in [7]. Previous studies have mainly focused on the influence of the stochastic nature of the material properties or on the performance of some parts of the wall assemblies.

As a rule of thumb, the view established among designers is that a 50 mm of interior insulation of mineral wool with a vapour barrier is a safe solution and can be easily applied as a retrofit measure in Estonia. For our case study the measurements were performed inside the retrofitted walls in the typical historic wooden apartment building [8]. After one and a half year, the occupants of the apartment started to complain about their children's health problems. The walls were opened and heavy mold growth was detected. Also, the opening of the retrofitted walls revealed differences between the design and the execution. The question about the reliability of the interior insulation arose. This paper analyses the probability of failure occurrence taking into account different scenarios regarding the interior thermal insulation used as a retrofit measure in historic wooden apartment buildings in cold climates.

2. Methods

Using a stochastic approach, the performance of the interior insulation as a retrofit measure in a historic wooden apartment building was analyzed. Based on the measurement results, the simulation model was validated in the WufiPro5.3 (WUFI) [9]. The calibrated model was used to calculate the temperature and RH conditions in the wall.

The outdoor climate conditions, indoor climate loads, different retrofitted wall assemblies and quality of workmanship were used as the varying input data parameters (see Fig. 1). The wall assembly with the average design values and with the average indoor temperature and moisture excess is considered as base case. The hygric properties of the material layers are described in more detailed manner in [9].

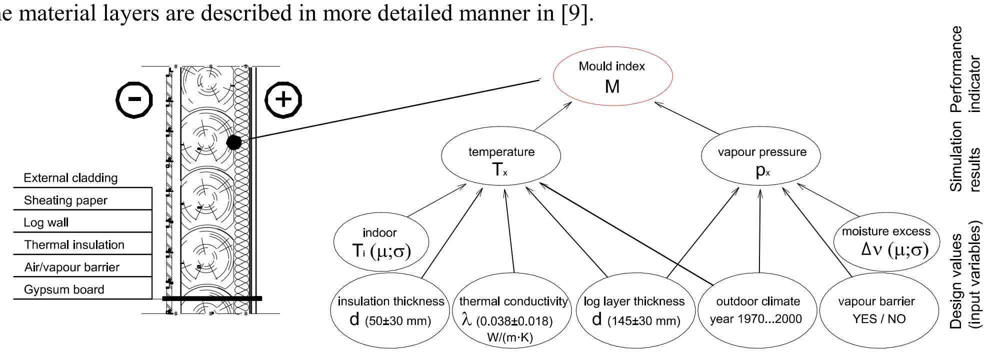

Figure 1. Design variables for the hygrothermal simulation model.

In this study the mold growth is considered as the performance indicator for risk assessment. According to [10], mould is one of the most hazardous contaminants of the indoor air and has to be prevented in any circumstances. Expected risk and durability of materials to mould growth can be predicted by calculating the mould index (*M index*) using the dynamic temperature and relative humidity histories of the subjected material surfaces [11]. *M index* was calculated using an improved mould growth model [12]. $M < 1$ represents conditions with no mould growth, $M = 1$ conditions with growth detectable with microscope, and $M \geq 3$ visually detectable mould growth on a wooden surface.

Uncertainty and variations in the distribution prevail in all the input data. The Monte Carlo method was used for sampling input variables according to their probabilistic distributions characteristics (Table 1). Sampling was done using random number generator. For the outdoor climate conditions, measured data from 30 years (from 1970 to 2000) were used for the simulations. Indoor climate conditions were simulated using the indoor hygrothermal load model for stochastic analyses presented in [13]. Altogether 100 combinations were generated and each combination represent an individual simulation.

The logistic regression analysis was used to estimate failure probability depending on different variables (Table 1). The WUFI simulations and the statistical computing environment R were used to calculate the logistic regression coefficients. For each input variable (see Fig.1), three values were selected (-1;0;1), for variables with normal distribution average ± standard deviation (st.dev) values were applied, for variables with uniform distribution min, avg and max values were used, and for the vapour barrier YES or NO was selected. All together 486 combination were generated and WUFI simulations was performed to check whether an unwanted outcome (*M index* >1) occurs or not.

Depending on the variables the probability for a solution to function without failure is between 0 and 100%. Using the regression coefficients, the probability of the unwanted outcome (*M index*>1) to occur can be calculated by equation:

$$p = \frac{e^{\left(\alpha+\beta_1 x_1+\beta_2 x_2+\beta_3 x_3+\ldots+\beta_n x_n\right)}}{1+e^{\left(\alpha+\beta_1 x_1+\beta_2 x_2+\beta_3 x_3+\ldots+\beta_n x_n\right)}} \tag{1}$$

where p is the probability that a case is in a particular category (*M index* > 1), e is the base of natural logarithms, α is the constant of the equation and β_i is the coefficients of the predictor variables x.

3. Results

In the first step for 100 randomly generated simulation cases the temperature and RH conditions inside the wall were simulated for one year period and the *M index* was calculated for all simulated cases. The *M indexes* calculated in first step for 100 randomly generated cases are presented in Figure 2. As a result of success (*M index*< 1) and failures (*M index* ≥ 1), it was found that the unwanted outcome occurred in 17 cases and 83 of the cases were safe. In 17 cases out of 100, a statistical probability of interior insulation failure is 17%. For 30 year calculation period the unwanted outcome occurred in 26 cases and 74 of the cases were safe, a statistical probability failure is 26%.

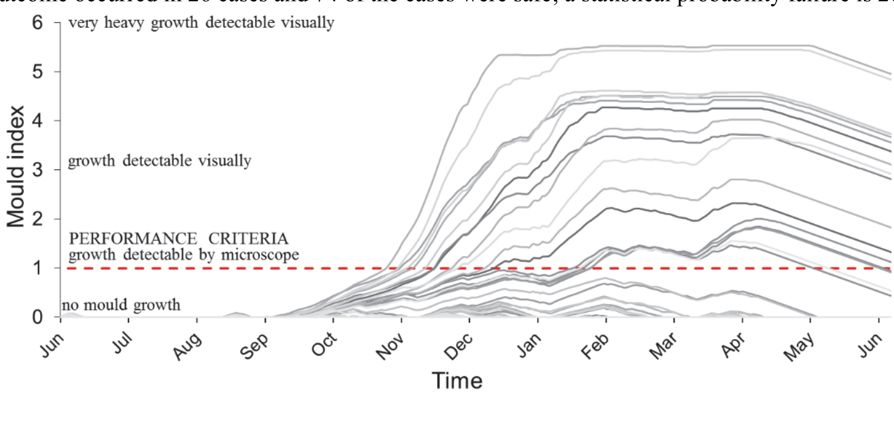

Figure 2. Calculated mould index between log and interior insulation layer of randomly generated 100 cases for one year period.

The coefficients returned from a logistic regression model are presented in Table 1. The coefficients express how the probability of the unwanted event to occur change with a one-unit change in the independent variable. In the studied case, the variable with the positive coefficient indicates that increasing the value of the variable raises the probability for the unwanted outcome (*M index>1*) to occur and the variable with the negative coefficient indicates that decreasing the value of the variable increases the probability of the event (*M index*>1) to occur.

Table 1. Probabilistic parameters and regression coefficients

Input variable	Design value and distribution*		*R* outcome		
			Coefficients	Standard error	p-value
Intercept			-2.578	0.458	$1.87\cdot10^{-8}$
Thickness of insulation layer (mm)	50±30	(*U min 20mm; max 80mm*)	6.373	0.876	$3.56\cdot10^{-13}$
Thermal conductivity λ (W/m·K)	0.038±0.018	(*U min 0.02; max 0.056*)	-6.709	0.918	$2.78\cdot10^{-13}$
Indoor temperature T_i (°C)	22.0±2.15	(*N* μ=22.0; σ_T =2.15)	-2.429	0.430	$1.59\cdot10^{-8}$
Moisture excess Δν (g/m^3)	2.51±1.07	(*N* μ=2.51; $\sigma_{\Delta\nu}$ =1.07)	4.051	0.603	$1.80\cdot10^{-11}$
Vapour barrier	1 / 0	(*D 1[yes] or 0 [no]*)	-4.757	0.779	$1.0\cdot10^{-9}$
Thickness of log layer (mm)	145±30	(*U min 115; max 175mm*)	-2.010	0.391	$2.75\cdot10^{-7}$

*explanation of distributions: *U* - uniform distribution between min and max value; *D* – discrete uniform distribution with option *a* and *b*; *N* – normal distribution with mean value (μ) ±standard deviation (σ).

Intercept gives the odds for the unwanted outcome to occur in the base case. The probability for *M index* >1 in the base case is 0%. If the vapour barrier is not installed or is broken, then the probability for a solution to fail (*M index* >1) is 7 %, in the 0.95 confidence intervals 3% to 19%.

In the sensitivity analyses, the existence of the vapour barrier is the most influential, because the wall is composed with exterior boarding that prevents the rain load and only moisture load is from indoors. In addition to the vapour barrier, the properties of the insulation material layer are of critical significance. From the boundary conditions, the value of the moisture excess has a higher effect than that of the indoor temperature. The change in probability of *M index*>1 in case of different insulation material layer thickness with and without vapour barrier in combination with average thermal conductivity, average log layer thickness and different indoor temperature (T_i) and moisture excess (Δν) is presented in Figure 3. For T_i and Δν the combinations of average ± st.dev values are considered ($T_{i\ avg}$; $T_i+\sigma_T$; $T_i-\sigma_T$; $\Delta\nu_{avg}$; $\Delta\nu+\sigma_{\Delta\nu}$; $\Delta\nu-\sigma_{\Delta\nu}$).

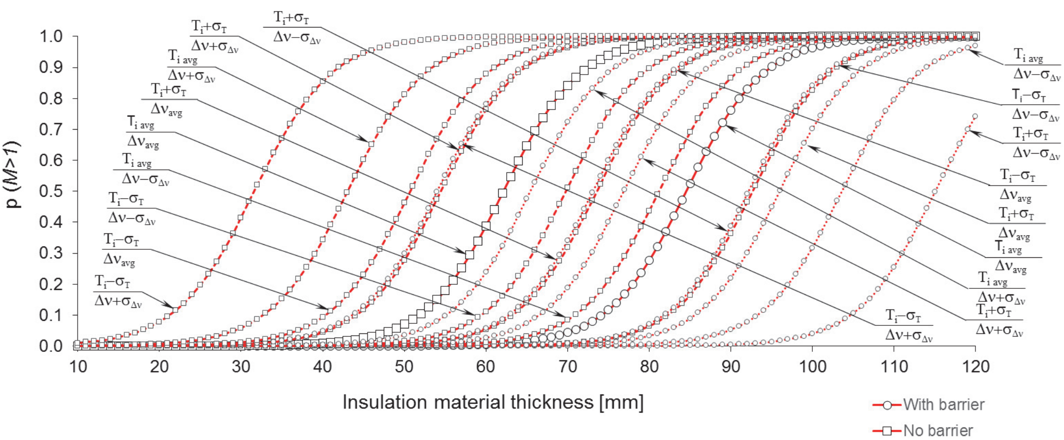

Figure 3. The change in probability of *M index*>1 in case of different input variables with and without vapour barrier.

To find the relation between the regressions analysis and the *M index*, the combinations of input variables generated for the first step WUFI simulations were used. The correlation between the calculated *M indexes* and the probabilities of a solution to function without failure of randomly generated 100 calculation cases are presented in Figure 4.

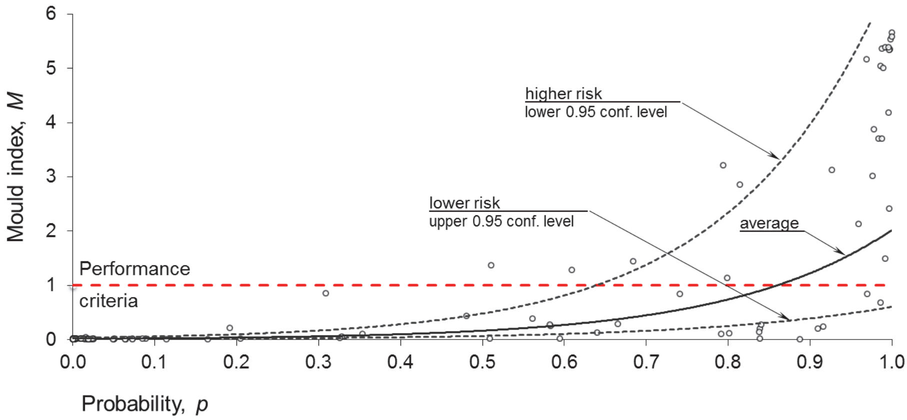

Figure 4. Correlation between the mould index and the probability of a solution to function without failure.

To assess the reliability, the boundary between safe and failure can be drawn in the intersection of the assessment criteria line and the probability line. The average probability for a solution to function without failure is 86% in the 0.95 confidence intervals 64% to 100%. Based on the stochastic calculations, at the safety margin set on the lower 0.95 confidence level, statistical probability to fail is 37% for the 50 mm thick interior insulation on the 145 mm thick log wall in typical indoor and outdoor climate conditions in Estonia.

4. Discussion

The study is limited to the historic wooden apartment buildings in cold climate. The study contains simplifications and assumptions. The applied retrofit measures are assumed to be installed in good quality. For probabilistic distribution characteristics the normal distribution is used for indoor temperature and moisture excess [10]. For thermal conductivity of insulation material, insulation material and log layer thicknesses uniform distribution (min, avg, max) is used to avoid preferring any certain values or value ranges. As a simplification, one type of vapour barrier (Z_p=0.96 (m^2•s•Pa)/kg; μ=190) was considered as installed or not (yes or no). "No" describes also a situation if barrier is broken.

The Spearman correlation (ρ) is used to evaluate the rank correlation between *M index* values (randomly generated simulation cases) calculated in the first step and calculated probabilities (based on the regression coefficients) in the second step. Spearman ρ assesses how well the relationship between the two variables can be described using a monotonic function. The critical values of the Spearman's correlation coefficient are presented in [14]. For probability of 0.0005 that the correlation occurred by chance the critical value ρ≥0.326 (sample size *n*=100). Values of the Spearman correlation close to 1 or -1 indicate high correlation between the compared indicators and values close to zero indicate low correlation. For the correlation between the *M indexes* and the probabilities the Spearman correlation indicates high monotony (ρ>0.82).

Presently, no generally accepted agreement on the acceptable failure % exist for the risk assessment. In [15] the use of 10% percentile as the critical level for the hygrothermal dimensioning of the building envelopes is recommended. It is crucial to set the acceptance criteria taking into account the risks to occupants and the risks regarding the economic aspects. If we can take risks considering economic aspects, then we cannot risk with people's health. But in both cases, even if the acceptable limit is set on 10% the probability of the interior insulation to fail is too high. To lower the risk of failure, the design values of the retrofit solution have to be changed and analyzed more deeply in further studies. It is required to take preventive measures appropriate to interior insulation. It can be assumed that concerning thermal insulation, thinner material layer or materials with higher thermal conductivity should be considered compared to base case. In addition, reduced moisture excess (ventilation system) and proper indoor temperature (heating system) are of high importance to ensure the performance of the interior insulation. Therefore, considering interior insulation as a retrofit measure it must be installed in combination with properly functioning ventilation and heating systems.

5. Conclusion

The probabilistic approach was applied to analyze the reliability of the interior thermal insulation as a retrofit measure for historic wooden apartment buildings. Statistical probability for the 50 mm thick interior insulation on the log wall in typical indoor and outdoor climate conditions in Estonia to fail is too high. The results of the stochastic study of the test walls show, a solution that involves design values and boundary conditions with possible distributions considered is unreliable for the interior insulation.

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PAPER IV

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Method for assessment of energy retrofit measures in milieu valuable buildings

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Abstract

Proposed method concentrates on the junctions of structures that usually have strongest influence on visual character of the building. To gain energy savings, a major change of the influence occurs when external thermal insulation is considered without any changes in other parts of the building. Whole building renovation is preferred because all the different parts of the building can be taken into account and the energy savings are larger and overall influence on the architectural appearance is smaller. Energy performance of the historic wooden buildings can be improved significantly without negative influence on the architectural appearance and destroying the milieu value of the district.

Keywords: energy retrofit; milieu value; historic building

1. Introduction

The average renovation rate in Europe is low, amounting to 1.2-1.4% per year. Thus it is estimated that by 2050, about half of the existing building stock in 2012 is expected still to be operational [1]. Energy Roadmap 2050 [2] states that the prime focus should remain on energy efficiency, where buildings play a major role. Buildings are responsible for 40% of energy consumption in Europe [3]. In Estonia the share of buildings is much higher than the EU average, amounting to 50.2%, in 2011 and 2012 it was slightly lower, about 48% [4]. Apartment buildings in Estonia account

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for 51% of the total net area of dwellings [5]. The average heating energy used in historic wooden apartment buildings in Estonia was 211 kWh/(m2 a) and the average primary energy consumption was 331 kWh/(m2·a) [6]. This is more than twice higher than that expected in today's new apartment buildings. Many studies [7-9] have indicated that the improvement of the building's shell of existing building stock hides large savings potentials.

Historic buildings are an important part of cultural heritage, the preservation of which is important for society and culture. It is our target to work out the principles and guidelines for the preservation of historic values for the future generations. Additional exterior thermal insulation of historic building is a challenge. It may cause a significant visual change as well as a loss in original material, thereby reducing the value of a historic building and conflicting with the preservation target. Consequently, in principle, in those buildings, such kind of insulation is rejected.

In addition to a single building, also a district can be valuable for its distinctive character. Important elements that express the character are defined mainly as an urban pattern, the formal appearance of buildings (both interior and exterior, defined by scale, size, style, construction, material, color and decoration) but also the various functions the area has acquired over the time [10]. In Estonia the valuable districts are protected as designated conservation areas or milieu valuable areas. Focus in this study is on historic buildings in milieu valuable areas (conservation areas), as the heritage restrictions are slightly milder (only the exterior of buildings is defined as valuable) and the buildings in milieu valuable areas are not merely protected.

In the near future, large number of the buildings in milieu valuable areas will require major renovation [11]. Historic buildings are subject to demands set by different regulations as thermal comfort, hygrothermal performance and energy efficiency regulations on the one hand and the heritage regulations on the other hand. Historic buildings are often seen as the conflict area of different parties because of the different standpoints. The owners and heritage authorities may not pursue the same goals when it comes to improving living conditions and energy efficiency and preservation of the historical buildings. Finding solutions to conflicts that arise when energy efficiency requirements are applied on architectural heritage is an acute research topic in many countries [12-17]. The majority of the abovementioned methods take into account single structures but seldom concentrate on junctions of structures that usually have the strongest influence on the visual character of the building. In current study a replica of an original solution is considered to be acceptable, assuming that construction works follow the best practice. A method to assess the influence of energy retrofit measures on the building level in the milieu valuable district is presented.

2. Method

In the renovation process, the first activity is to define the need for renovation and the assessment criteria for renovation measures. The need for renovation can be viewed from the following aspects: A)Urgent repairs to guarantee safety of buildings (mechanical resistance and stability, safety in use, safety in case of fire); B) Improvement of indoor climate (hygiene and health aspects, fulfilment of requirements to ventilation air rates and room temperatures; protection against noise); C) Improvement of energy performance of a building as well sustainable use of natural sources; D) Improvement of architectural planning, visual quality, overall living quality, and additional comfort.

Safety aspects (A) and requirements for the indoor climate (B) are usually well-defined in laws and decrees. Commonly these are mandatory without large deviations. National legislation based on the Energy Performance of Buildings Directive [4] sets common targets for the energy performance of buildings (C). Even directive and national legislation provides an exception for buildings with special architectural or historical merit, owners and inhabitants have increased interest and willingness to invest in energy saving solutions to decrease expenses for energy, to make renovation more cost effective and to live in a more environmentally friendly building. The indoor climate and energy audits show the need for improvement of the indoor climate and the energy performance of a building. To assess the need for improvement of the indoor climate, indoor air quality and thermal comfort in selected apartments should be measured. The energy audit is specially needed, when partial renovation is planned. For deep renovation of a whole building, pre-renovation energy consumption is rarely needed, it is required when the relative decrease of energy consumption is needed. In addition, human requirements and needs (D) can change over time and cause the need for renovation.

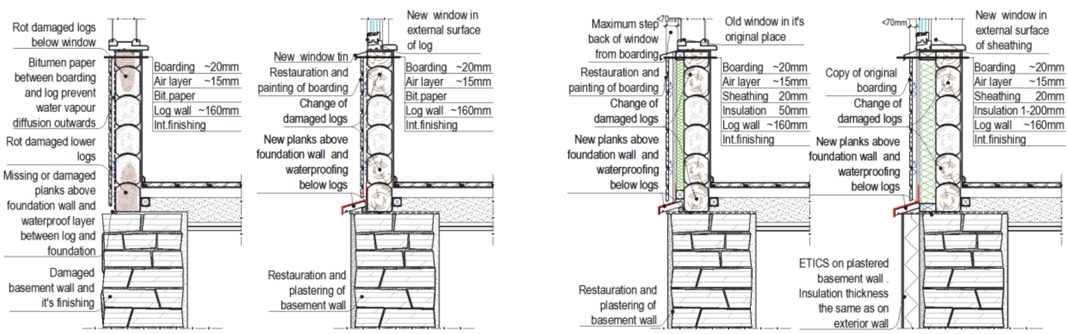
Methodologically, assessment of heritage values is a complex process since subjective evaluations cannot be ruled out entirely. Commonly, a wide range of qualitative methodological approaches are used to assess the heritage values.

The conservation field has traditionally relied on expert appraisals [18]. In current study the subjective evaluation also relies on an expert assessment (Table 1, Fig.1).

Table 1. Evaluation matrix for energy retrofit measures.

Other structures	Exterior wall							
Starting conditions of the building: 1 - original facade; –1 - façade in typical condition; –3 - old façade not original. Grades to retrofit measures: 0 - no influence; –1 - undetectable influence; –3 - tolerable influence; –5 - strong negative influence; –7 - intolerable influence. Assumptions: - replica of original solution is acceptable; - construction works follows the best practice.	Original facade	Typical condition [11]	Old facade (not original)	Replica of original facade, no insulation	EW20. External wall +20mm insulation: U 0.51 W/(m^2×K)	EW70. External wall +70mm insulation: U 0.34 W/(m^2×K)	EW120. External wall +120mm insulation: U 0.24 W/(m^2×K)	EW170. External wall +170mm insulation: U 0.19 W/(m^2×K)
AF0. Original attic floor	1	-1	-3	1	-1	-3	-5	-7
AF200. Attic floor /roof: +200mm insulation: *U 0.17 W/(m^2×K)**	1	-1	-3	1	-1	-3 / -1	-5 / -1	-7 / -1
AF400. Attic floor /roof: +400mm insulation: *U 0.11 W/(m^2×K)**	1	-1	-3	1	-1	-3 / -1	-5 / --	-7 / -1
BF0. Original basement ceiling	1	0	0	0	0	0	0	0
BF100. Basement ceiling: +100mm insulation: *U 0.21 W/(m^2×K)*	1	0	0	0	0	0	0	0
W2.8. Original window in original place: *U 2.8 W/(m^2×K)*	1	-1	-3	1	-1	-3	-5	-7
W1.8. Window renovation: in original place *U 1.8 W/(m^2×K)*	1	-1	-3	1	-1	-3	-5	-7
W1.4. Window replacement: new window *U 1.4 W/(m^2×K)***	-1	-1	-3	0	-1	-3 / -1	-5 / -1	-7 / -1
W1.1. Window replacement: new window *U 1.1 W/(m^2×K)***	-1	-3	-3	0	-2	-3 / -2	-5 / -2	-7 / -2
BW0. Basement wall, no insulation (original)	1	-1	-1	-1	-1	-3	-5	-7
BW70. Basement wall +70mm insulation: *U 0.34 W/(m^2×K)*	-3	-3	-3	-3	-3	-1	-3	-5
BW120. Basement wall +120mm insulation: *U 0.24 W/(m^2×K)*	-5	-5	-5	-5	-5	-3	-1	-3
BW170. Basement wall +170mm insulation: *U 0.24 W/(m^2×K)*	-7	-7	-7	-7	-7	-5	-3	-1

* eaves left in original place / eaves and rafters lengthened; **new window installed in place of original window / new in new place (Fig.1, d)



a) Original materials, appearance, structure, details and relationships of building elements influence on the milieu value of the district.

b) The change of window: minor influence on the appearance

c) Additional thermal insulation on walls up to 50mm + sheathing (windows step back up to 70mm; minimum basement wall's step forward): some influence on the appearance

d) The change of window and additional thermal insulation on walls, windows moved outward: minor influence on the appearance

Fig. 1 Different energy renovation measures and their influence on architectural appearance.

To assess the influence of the building renovation measures on the milieu of the district, the values of external appearance of the buildings should be defined. Values can be defined by an inventory of renovated building, the districts, where the building is located or of similar buildings in other districts. Values can be defined through external appearance, details of structures, materials, profile of boarding, coloring etc. It is important to understand that also the influence of possible differences from the original and the best solution should be defined. Thus, a multi-criteria analysis is required, which different aspects can most properly be taken into account in the final solution.

First of all, the acceptable changes in the visual appearance have to be defined in the assessment. If an assumption is made that additional thermal insulation on the exterior of the building and replica of the original cladding are allowed, then the focus is on the junctions of the building constructions (wall and window; wall and roof; external wall and basement wall). In this study, many onsite measurements were conducted to set the limits for different junctions' protrude and retreat to define the characteristics of the buildings. Based on the measurements and expert assessments, an evaluation matrix was composed to analyze the influence of different retrofit measures on the characteristics of the building (Table 1, Fig.1).

3. Case study

The usability of the method was tested on a milieu valuable district of historic wooden apartment buildings in Tallinn. A Lender-type wooden apartment building was chosen for the case study (Fig.2). These buildings were widely spread in Tallinn at the end of the 19th century and at the beginning of the 20th century, demonstrating industrial development and general urbanization of Estonia. However, after the industrialized construction period between 1960…1990 wooden apartment buildings were rather disgraced and not maintained property. Today these districts are very popular and many people are buying apartments in these buildings willing to renovate their own property.

Fig. 2 Visual character of the building in the milieu valuable district before renovation (left) and after renovation (right).

Table 2 shows how and to what extent the method was used to take into account all the different aspects for the assessment of the energy renovation measures in a historic wooden apartment building.

Within the determination of the need for renovation (thermal comfort, energy performance) grades were given to the renovation solutions, based on their influence on the milieu values. Under different scales, the influence can be positive, neutral or negative. For example, the positive effect implies that the original external appearance is restored: unsuitable cladding is replaced with the replica of historic cladding and with original detailing. The neutral effect implies that the original external appearance is restored without replacement of materials or changes of colors. Basically, this means cleaning and painting of the building with replacement of damaged structures. Minor negative influence (Fig.1, b) means some building elements have been replaced for similar but modern ones. For example old damaged and leaky windows are replaced with new and energy efficient windows and installed in their original place. Slightly stronger influence (Fig. 1, c) on the milieu of the district is observed if the relationships between different structures and building elements change. There are three critical junctions on the façade of the building in the case of a Lender- type building: the basement wall and the external wall; the window and the external wall; the external wall and the eave. Typically, in that type of a building the basement wall protrudes the external wall, the windows are located in the same plane with the external wall cladding without any protrude or step back, and the eaves have decorated rafters. The inventory of wooden apartment buildings, made by professional conservators, concluded that up to 7 cm step back in the case of window fem boarding is still acceptable in terms of milieu values. Thus, a thin additional thermal insulation layer can be installed without moving windows or changing the basement wall or the eave. When the whole building (Fig. 1, d) is under renovation all at once, it is possible to guarantee, that all materials, relationships between different building structures and elements can be preserved and only minor changes influence the milieu of the district.

Table 2 Determination of the current situation and renovation solutions.

	Topic	Target	Basis of current study
A	Technical condition and the need for renovation of wooden apartment buildings	Fulfilment of essential requirements on the performance criteria of the building	The deep technical survey of 29 apartment buildings; the overall technical state and the most common areas requiring improvement is based on a survey of 133 apartment buildings in four towns [11].
B	Indoor climate	The current state and need for improvement of indoor climate	Measurements of indoor temperature and relative humidity, air change rate, air quality and user satisfaction
C	Solutions for energy economic renovation	The influence of single renovation measures and renovation packages on the use of energy	Measurement of energy use before renovation in 29 buildings and calculations of energy economic renovation of four typical apartment buildings [6]; insulation solutions to improve energy efficiency and thermal comfort
D	Values and valuable details of building	Determination of values to be saved and improved; possible changes as well as their influence on the heritage value	The survey of wooden apartment buildings; inquiry about the milieu valuable buildings and how different people perceive the milieu valuable areas and values concerning buildings

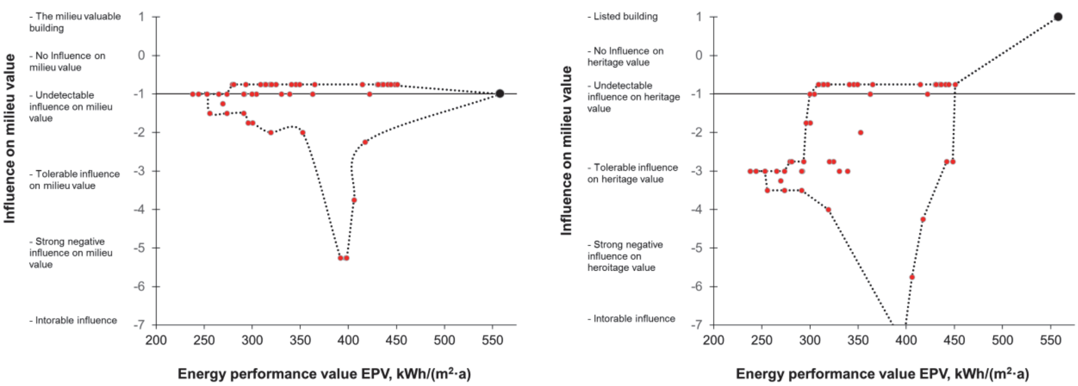


Fig. 3 Influence of the energy performance improvement on the architectural appearance of the building.

Different renovation packages were considered to find out the improvement of the energy performance and the influence on the characteristics of the building. Since the architectural appearance of a building is regarded valuable, the packages consisting of insulation measures were assessed. The grade expresses the alteration of the milieu value of the building. First, the average grade for the whole building is calculated taking into account all the single renovation measures in the specific renovation package and their influence on the different junctions of the building (Table 1). In addition, if the additional thermal insulation of external wall is considered, then the grade of the starting condition of the façade is subtracted from the calculated average grade.

The results of the improvement in the energy performance value and the influence on the milieu value are presented in Figure 3. For the energy performance the simulation software IDA Indoor Climate and Energy 4.5.1 was used and the simulations are described in more detailed manner in [6]. The starting point for the energy performance value is

558 kWh/(m^2·a). The influence is presented in two different cases, first for a building in typical condition that needs to be repaired in the near future (Fig. 3 left), and second, for a building in a good condition, where renovation is motivated to improve the energy performances and thermal comfort (Fig. 3 right).

The starting condition of the building has a strong influence on the overall grade of the renovation measures. To gain moderate savings, out of single or couple insulation measures, the measures less visible should be preferred. Under larger energy savings by applying few measures, a major change of the influence occurs when the external thermal insulation is considered without any changes in other constructions or junctions connected to the external wall. But in both cases the whole building renovation is preferred when the energy savings are larger and the overall influence on the milieu value is smaller. The reason is that when renovating the whole building, all the different parts of the building are taken into account and it is easier to solve the junctions of the façade elements without degrading the architectural appearance of the building.

4. Conclusion

In the near future large number of the buildings in milieu valuable areas will require renovation. Historic buildings are subject to demands set by different regulations, energy efficiency regulations on the one hand and the heritage regulations on the other hand. A method to assess the influence of energy retrofit measures on the building level in the milieu valuable district was introduced and tested. Different renovation packages were analyzed to find possible changes in building appearance. Independent of the starting conditions, the whole building renovation is preferred over single insulation measures that are visually easier to detect. Our results show that the energy performance of the historic wooden apartment buildings can be improved significantly without negative influence on the architectural appearance and destroying the milieu value of the district.

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PAPER V

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Field Study of Hygrothermal Performance of Log Wall with Internal Thermal Insulation

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ABSTRACT

The energy efficiency of old wooden apartment buildings built before the Second World War need to be improved to save energy and increase thermal comfort. According to the regulations no changes outside the external wall on the facade are permitted. Internal insulation is a possible solution when the external style has a high value and must be preserved. Internal insulation consists high hygrothermal risks. This paper analyzes the measurement results of the temperature and RH of an internally insulated log wall. Six different solutions were used to insulate the log wall: three different insulation materials together with and without air/vapour barrier were used. According to the measurement results there is a high risk of condensation and mould growth inside the wall in dwellings with high humidity load. In the studied case the durability of the renovation solutions is questionable because the measurement results show inadequate hygrothermal performance of the internally insulated log wall. Based on the mould growth model, in all the cases the temperature and RH level inside the wall between the insulation layer and the log layer exceeded the temperature and relative humidity conditions favouring initiation of mould growth more than 75% of the time. To use the internal insulation it is recommended to lower the vapour pressure inside the wall by reducing the moisture excess inside the room by installing a mechanical ventilation system or increasing the vapour resistance by adding vapour retarding foil to the warm side of the insulation layer.

KEYWORDS

Hygrothermal performance, mould growth, internal insulation, wooden apartment building.

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1 INTRODUCTION

The wooden apartment building was the prevalent building type before World War 2 in the suburbs of many towns in Estonia. Currently these areas are listed as milieu or culturally valuable areas with specific planning and building regulations set to preserve the existing environment. The majority of old wooden apartment buildings have massive log (thickness typically 12-15 cm) walls without any additional thermal insulation. Walls are covered with external wooden cladding and internal plaster layers. Thermal transmittance of these types of walls is U_{walls}≈0.6…0.7 W/(m^2·K). The average air leakage value of the building envelope is n_{50}≈17 h^{-1}.

Estonian (57…59 N; 22…28 E) climate is characterized by cold and humid winters and warm summers with the average annual temperature +5.6 °C. The annual average number of heating degree-days tin S for indoor balance temperature of +17°C is 4249 days. Due to cold climate buildings are heated during winter.

In view of the fast increasing energy prices, living in buildings with low energy efficiency can become a very expensive ”pleasure”. By improving the building envelope with additional insulation, it is possible to save energy and increase thermal comfort.

Due to the regulations no changes outside the external wall on the facade are allowed to be done. Internal insulation is a possible solution when the external style has a high value and must be preserved. Internal thermal insulation may cause hygrothermal risks and special requirements for the properties of other material layers. The low temperature of the log layer has an effect on the partial vapour pressure conditions and can cause moisture risks on the log layer [Ojanen 2007]. It is possible to eliminate the problem of moisture diffusion with vapour retarder, but the problem with moisture convection may stay still [Ojanen and Simonson 1995]. External thermal insulation is a hygrothermally much safer solution compared to internal thermal insulation.

Nevertheless, many studies [Stopp, et al. 2001, Madĕra 2003, 2003, Häupt et al. 2004, Juhart et al.2005, Toman et al. 2009] have analysed the possibilities to use the internal thermal insulation for improving external wall structures. Even if the risks and solutions of internal thermal insulation are presented, most of these studies are concentrated on stone walls, as a typical wall structure in Central Europe, but many to the log walls. Saarimaa et al. 1985 and Koski et al. 1997 have analysed hygrothermal performance of additionally insulated log walls in Finland by visual inspection and mostly by momentary measurement of moisture content. It is possible to study many buildings with momentary measurement, but it is not clear if the measurement period is sufficiently critical over the whole year. Therefore long-term measurements are needed. Comparison of different materials and envelope solutions is necessary because they affect hygrothermal performance in different ways.

In this study six solutions of internal thermal insulation for the log wall are analysed based on follow-up field measurements. Hygrothermal performance is analysed based on the temperature and relative humidity measurements in the wall. Durability of refurbishment solutions is assessed in terms of the risk for mould growth and condensation inside the wall.

2 METHODS

2.1 Studied Wooden Apartment Building

The measurements were carried out in a typical wooden apartment building called “Lenderi Maja”, situated in a milieu valuable area in Tallinn. The building originates from the beginning of the 20th century. The building has two floors and a cellar, apartments are heated by stove and electrical radiators. There is a natural passive stack ventilation system in apartment with mechanical exhaust fans in the toilets (not permanently used). The test wall was situated in apartment 1 (on the first floor) on north-facing wall of the main bedroom.

The apartment building was studied under a larger national research project focused on the technical condition and service life of Estonian wooden apartment buildings. The building was under renovation and occupants decided to insulate walls with internal mineral wool insulation. After discussion, the occupants promised to conduct the follow-up measurements about the hygrothermal performance of the wall with internal insulation.

2.2 Studied Test Walls

The initial log wall construction consisted of a 140 mm log sealed with a tow and covered externally with sheathing paper and 20-mm wooden cladding.

Six different insulation solutions were analysed. The size of the analysed wall section was 60×60cm. All wall sections faced to the same wall of the bedroom. Test walls were separated by metal battens and polyurethane foam tightening. The solutions differed in the insulation materials and air barriers that were used, see Figure 1.

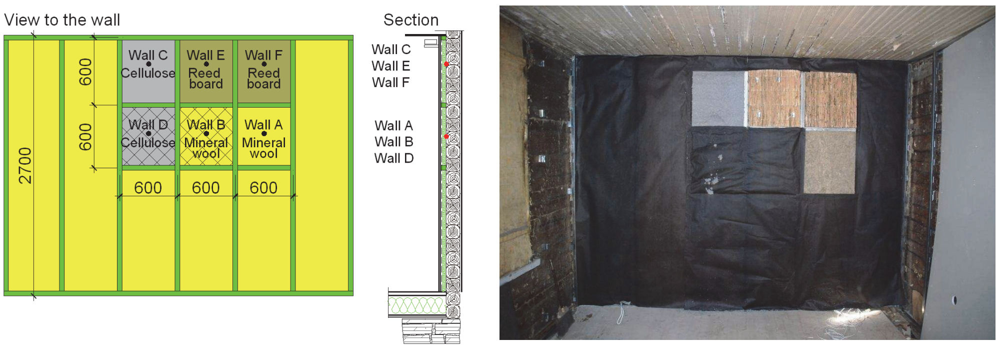

Figure 1. Temperature and relative humidity sensor positions on the log layer before the added insulation material (left) and a view of the insulated wall before the finishing layer (right).

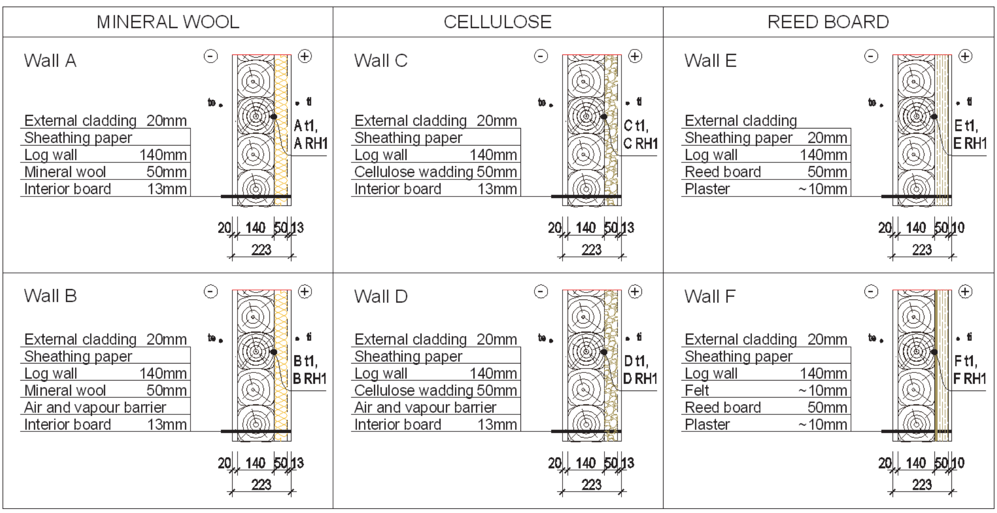

Figure 2. Sections of the studied test walls.

Altogether three different insulation materials were used: reed insulation mat (λ_{reed}≈0.054 W/(K·m)), cellulose insulation ($\lambda_{cellulose}$≈0.045 W/(K·m)), and mineral wool (λ_{mv}≈0.040 W/(K·m)). Insulation materials were used with and without air barrier and were finished inside the room with gypsum board or render. Air barrier paper impregnated with bitumen (Z_p $0.6 \cdot 10^9$ m^2sPa/kg) was used as an air barrier between the inside sheathing and the insulation material. Sections of the insulated log wall are shown in Figure 2.

2.3 Measurements

The values of temperature and relative humidity (RH) were measured with Ø 5mm sensors (Rotronic Hygroclip SC05; measurement range: –30 °C…+100 °C, 0…100 % RH with accuracy ±0.3 °C, ±1.5 % RH) inside the wall between the additional thermal insulation layer and the log layer (see Figure 2) and saved with a data logger. Temperature and RH inside the bedroom and outside the building were measured with data loggers (Hobo U12-013; measurement range -20…+70 °C; 5…95% RH, with an accuracy of ±0.35 °C; ±2.5% RH). All the measurements were taken at a one-hour intervals. The indoor data logger was placed in the middle of the bedroom and an outdoor temperature data logger was placed on the north facade of the building, protected from direct solar radiation.

2.4 Assessment of risk for mould growth

The risk of mould growth assessed according to the experiments reported in [Hukka & Viitanen 1999] suggest that covering the temperature range of 5-40°C the boundary curve for the risk of mould growth on a wooden material can be described by a polynomial function:

$$RH_{crit} = \begin{cases} -0.00267 \cdot t^3 + 0.160 \cdot t^2 - 3.13 \cdot t + 100 & ,when\ t \leq 20°C \\ 80\% & ,when\ t > 20°C \end{cases}$$

The time of the temperature and RH conditions favourable for mould growth during the measurement period was calculated.

3 RESULTS

3.1 Climate Condition

Hourly temperature and RH's data measurements were taken and collected through out a near one-year period: 12.12.2009…6.10.2010. Outdoor temperature during the measurement period varied between -21.5°C…+33.6°C and RH between 22%...100%. During winter the average temperature was -7.4°C (min. -21.5°C, max. +4.2°C) and RH 89% (min. 62%, max. 100%). The annual indoor temperature in the bedroom varied between +13.5°C…+27.5°C and RH between 43%...83%. During winter months the average temperature was +17.4°C (min. +13.5°C, max. +24.5°C) and RH 64% (min. 43%, max. 74%).

Figure 3 left shows the dependence of the indoor temperature on the outdoor temperature. Each dot represents the measured value corresponding to the outdoor temperature. The indoor temperature depends quite linearly on the outdoor temperature. This indicates to problems with sufficient heating power of the heating system. The average indoor temperature stays below the lowest category of thermal comfort 50 % of the time during winter due to low indoor temperatures.

It is important to know the humidity load to assess the hygrothermal performance of the wall. Humidity loads are presented as internal moisture excess that shows the difference between the indoor and outdoor air humidity by volume. Dependence of the moisture excess on the outdoor temperature is shown in Figure 3 right. From this data, the 90 % critical level [Sanders, 1996] was calculated (black dotted line). This level means that hygrothermal loads higher than the determined critical value should not exceed 10% of the cases. During cold periods the weekly average internal moisture excess is between +7 g/m^3. Based on earlier studies in Estonian dwellings [Kalamees 2006], the studied apartment may be classified as a dwelling with a very high humidity load. The humidity load was high due to low ventilation (natural ventilation), higher occupancy (23 m^2/pers.), and possible drying out of structural moisture.

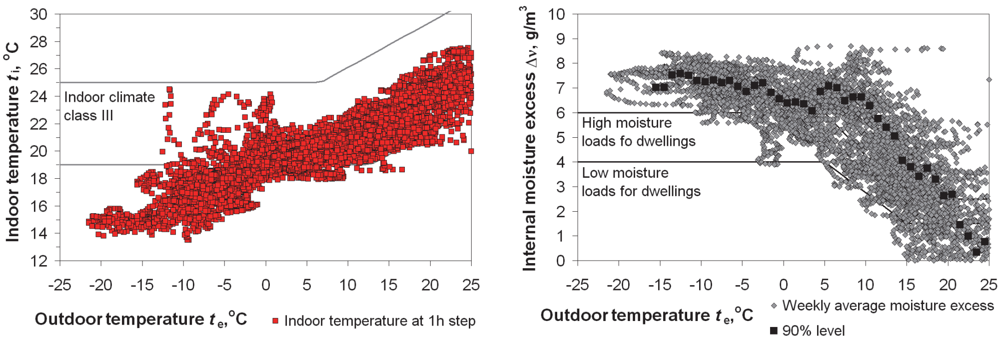

Figure 3. Dependence of the indoor temperature and moisture excess on outdoor temperature.

Due to low temperature and high humidity loads, indoor RH was high during cold period, Figure 4. The indoor RH stays above the criteria for indoor RH during winter in Estonia (RH 25…45%) most of the time.

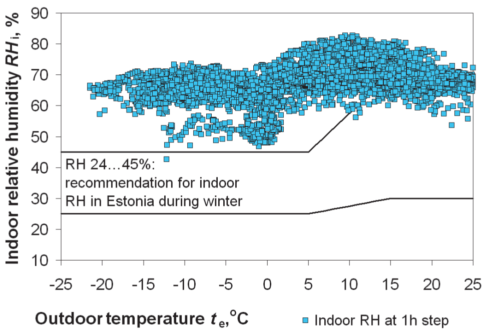

Figure 4. Dependence of the indoor RH on the outdoor temperature.

3.2 Hygrothermal Condition Inside the Wall

Reference point to assess the hygrothermal performance of the internally insulated wall was between the original log and the internal insulation.

Indoor and outdoor temperature as well as temperatures inside the wall between the insulation material and the log layer is shown in Figure 5 left. Steady-state distributions of temperature during February are shown in Figure 5 right. During the measurement period, the lowest temperature on the internal surface of the log was observed in the case of mineral wool insulation. This corresponds also well to the lowest thermal conductivity of this insulation material.

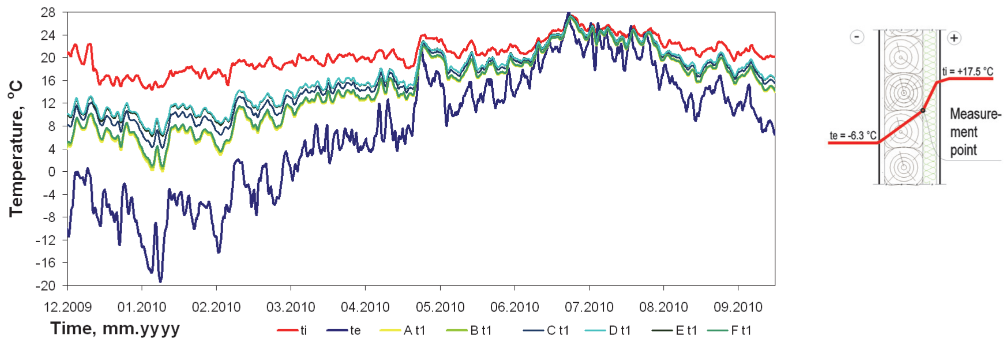

Figure 5. Measured daily running-average temperatures (left). The distribution of average temperature during February (right).

RH was high through out the winter-spring period, Figure 6. RH was close to the upper measurement limit, indicating possible moisture condensation to the inner surface of the log. Also, the calculated steady-state vapour distribution in the wall indicated possible moisture condensation in the wall between the insulation material and the log layer. The RH was highest in test walls with mineral wool insulation. On the other hand, test walls with mineral wool insulation dried more quickly than the wall with cellulose or reed insulation mat during summer period.

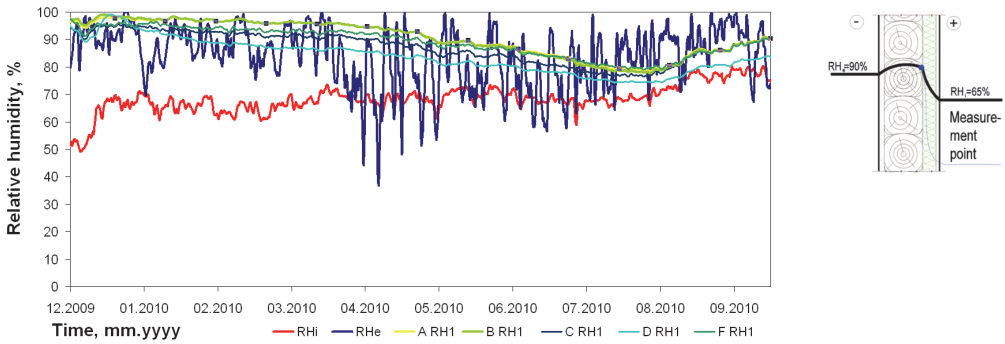

Figure 6. Measured daily running-average RH (left). The distribution of average RH during February (right).

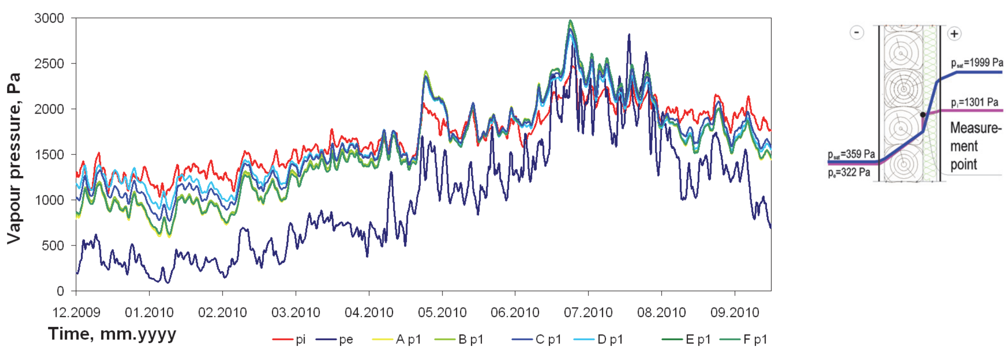

Figure 7. Measured daily running-average water vapour pressures (left). The distribution of average water vapour pressure during February (right).

Water vapour pressure on the indoor and outdoor air as well as inside the wall between the insulation layer and the log layer are presented in Figure 7. During the spring-summer period the air vapour pressure inside the wall was higher than the air vapour pressure in the bedroom, indicating the drying of the wall to the indoor air. Water vapour pressure was higher in the test walls with hygroscopic thermal insulation.

As the air pressure difference across the structure was ±2…3 Pa the main moisture transport mechanism is assumed water vapour diffusion.

The RH on the inner surface of the log wall stays at the high level during the whole measurement period. Based on the mould growth model [Hukka and Viitanen 1999] in all the cases, the temperature and RH level inside the wall exceeded the temperature and relative humidity conditions favouring initiation of mould growth on wooden materials, see Figure 8.

In the case of the mineral wool insulation temperature and RH conditions are favourable for mould growth more than 88% of the time. With cellulose insulation the risk for mould growth is higher in walls without air- and vapour barrier (84 % of measured time length) than with air- and vapour barrier (75 % of measured time length). With the reed insulation mat more than 93% of the time is favourable for mould growth.

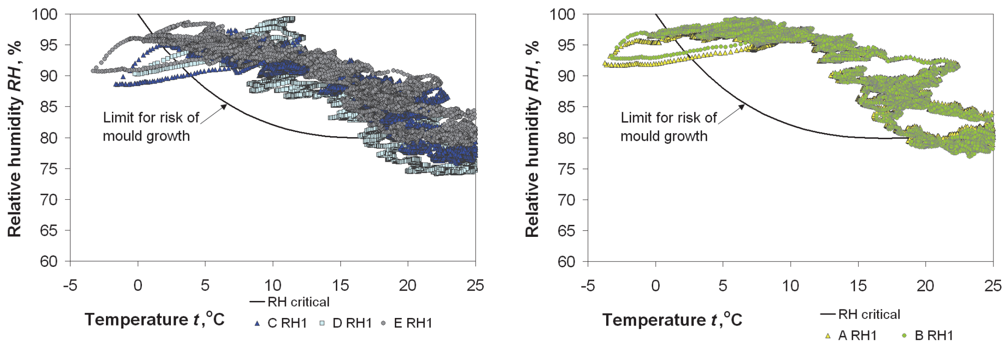

Figure 8. Temperature and RH conditions are favourable for mould growth for "green" insulations (left) and for mineral wool (right).

According to the mould growth assessment, there should be a high risk for mould growth. Nevertheless, the wall was not opened for examination. No visual inspections were done and no mould could be observed.

4 DISCUSSION

Field measurements showed a high humidity level in the internally insulated log wall. Hygrothermal conditions on the inner surface of the log wall were favourable for mould growth in all test walls. Insulation material (hygroscopic or not) did not significantly lower the risk for mould growth. Different test walls were separated by metal battens and polyurethane foam tightening to prevent diffusion and conduction between the test walls. Although there may have been some minor leaks between the test walls, the potential for the diffusion and conduction was low and possible heat and moisture movement between the test walls was probably minor.

Some earlier studies carried out in wooden buildings in cold climate conditions have shown the possibilities to assemble additional insulation layer inside a log wall without a vapour barrier [Saarimaa *et al.* 1985; Koski *et al.* 1997]. According to Saarimaa [1985] it is possible to use internal insulation without vapour barrier but there were too many uncertainties to be convinced that the measurement results assure it. According to Koski [1997] no hygrothermal problems occurred with log walls with internal insulation. Neither was there great differences discovered between the log wall with a vapor barrier and without a vapor barrier. The main reason for that was the internal sheeting. The internal sheeting proved to have a rather high vapor resistance compared to the sheeting used in this study. The internal sheeting had about five times higher vapour resistance than a gypsum board. Nevertheless the results obtained in the studies referred to were not based on many long-term measurements in dwellings with high humidity loads. To work out viable renovation solutions critical boundary conditions should be obtained.

The test walls studied were located in apartments with high humidity loads. This was caused mainly due to low air change rate (natural ventilation) because the ventilation system was not renovated. Therefore, to guarantee good indoor climate and energy efficiency of buildings, the following three components must be maintained in the process of renovation:

- hygrothermal performance of building envelope;
- performance of ventilation;
- performance of heating systems.

5 CONCLUSION

The measurement results of the temperature and RH of the internally insulated log wall were analysed. All the test walls with different thermal insulation resulted in high humidity levels that were favourable for mould growth on wooden material more than 75%...80% of the time. It was found that the vapour permeable air barrier paper mounted between the insulation material and the finishing layer has very low impact on the RH levels inside the wall and has no impact on temperature. High RH levels between the insulation material and the log layer correspond to the calculated steady-state winter conditions where the partial vapour pressure in the wall between the insulation material layer and the log layer exceeds the saturation pressure level. The internal insulation of the log wall could be used if the vapour pressure inside the wall is lowered. Thus the moisture excess inside the room by installing a mechanical ventilation system is reduced or the diffusion resistance by adding vapour retarding foil to the warm side of the insulation layer is increased.

Even the internal thermal insulation seems to be a possible solution when the external style has a high value and must be preserved, the solution should be carefully calculated in order to prevent occurrence of hygrothermally critical conditions. In the studied case the durability of the renovation solutions is questionable because the measurement results show inadequate hygrothermal performance of the internally insulated log wall. In addition, the high risk of mould growth can lead to mould problems that can cause health problems for the inhabitants of the apartment.

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PAPER VI

Arumägi E, Kalamees T. (2012) Validation of a Simulation Model for Hygrothermal Performance of Log Wall with Internal Thermal Insulation in Cold Climate. In Proc. of the 5th International Building Physics Conference. Kyoto 2012

Validation of a Simulation Model for Hygrothermal Performance of Log Wall with Internal Thermal Insulation in Cold Climate

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Keywords: internal insulation, hygrothermal simulations, field tests model validation, renovation

ABSTRACT

Today there are different computer programs for the hygrothermal analysis of the building envelope to help architects and engineers during design processes. It is economical and more efficient to use the simulation tools for assessing different retrofitting solutions compared to in situ measurements. The decisions made depend on the performance of the simulation model. Among other input data the material properties of the wall assemblies are required to make the simulations. The data influencing moisture transport can be introduced differently in the program. The quality of the results depends on the input variables, on the assumptions and simplifications made. A good correlation between the calculated results and measured values was achieved after the modification of the material properties and adding a factor as air change rate in the material layers inside the wall. Drying and wetting are determined more accurately if the convective air flow is included in the hygrothermal simulation model.

The HAM-calculation program WufiPro5.1 was selected for the investigation of the hygrothermal performance of the internally insulated log wall. Long-term temperature and relative humidity measurements inside the retrofitted log wall were used to validate the hygrothermal simulation model. The objective of this paper is to describe the validation of the simulation model against field measurements.

1. Introduction

Today there are different simulation programs for the hygrothermal analysis of the building envelope to help architects and engineers during design processes. With the simulation programs it is possible to assess the heat, air, and moisture flow through the building envelope in different climatic conditions. The program can also help to select renovation solutions with respect to the hygrothermal response of building assemblies subjected to various climates.

Results of the simulations are influenced by different input data, such as wall construction details, material properties, initial conditions, and climate conditions. For more reliable results the simulation models need to be validated based on laboratory or field tests.

This paper presents the validation of the simulation model of internally insulated log walls based on field measurements. After the validation, the simulation model will be used to study the hygrothermal performance of different renovation solutions and the influence of different boundary conditions. The final purpose is to work out hygrothermally "safe" solutions, for example to avoid mould growth or internal condensation in the wall.

1.1 Background

The energy performance of existing buildings needs to be improved to save energy and increase thermal comfort. The wooden apartment building selected for research object in this study was the prevalent building type before World War II in the suburbs of many towns in Estonia. Currently these areas are historic listed areas with specific planning and building regulations set to preserve the existing environment. According to regulations no changes to the façade are permitted. Internal insulation is a possible solution when the external style has a high value and must be preserved. The internal insulation is highly susceptible to hygrothermal risks in a cold climate. By changing the building to be more energy efficient, the hygrothermal conditions of the existing external wall change.

It is not economical and not even always possible to use in situ measurements for the assessment of the hygrothermal performance of the wall. The HAM-calculation program has good tools to investigate the hygrothermal performance of the wall.

1.2 Preliminary study

The study started with long-term field measurements of hygrothermal performance of the internally insulated log wall (Arumägi 2011). The values of temperature and relative humidity (RH) were measured inside the wall between the additional thermal insulation layer and the log layer. Also, the indoor and outdoor climate was measured. The durability of the renovation solutions is questionable because the measurement results show inadequate hygrothermal performance of the internally insulated log wall: there was high risk of condensation and mould growth inside the wall. Based on the mould growth model (Hukka and Viitanen 1999), the mould index for different walls raised to values from 4,6 to 5,3.

2. Methods

2.1 Studied walls

The140 mm thick log wall was sealed with a tow and covered externally with sheathing paper and 20-mm wooden cladding. Wall was internally insulated with three different 50mm thick insulation materials: reed insulation mat, cellulose insulation and mineral wool. Insulation materials were covered inside the room with air barrier paper, gypsum board (render in case of reed). The sections of the studied walls are presented in Fig. 1.

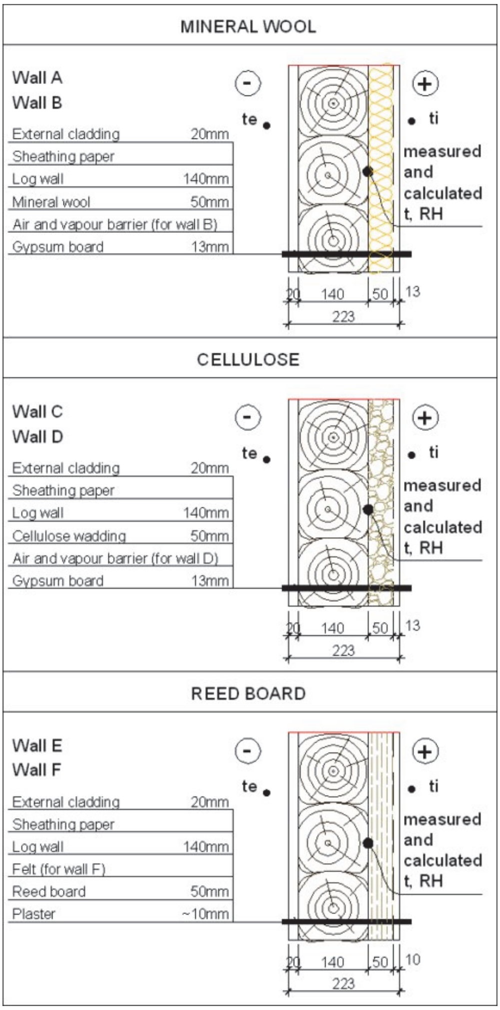


Fig. 1 The sections of the studied test wall.

2.1.1 *Simulation model*

The WufiPro5.1 (WUFI) was selected for the hygrothermal analysis. Comparison between calculation results against field measurements using WUFI simulation tool has shown a good correlation (Kalamees 2003, Hägerstedt 2011).

The program introduces two potentials for moisture flow: the liquid transport flux depends on relative humidity and the water vapour diffusion flux depends on vapour pressure. The airflow is not considered in the assessment of moisture behaviour.

The governing equations employed in the WUFI model for mass and energy transfer are as follows (Künzel 2000):

Moisture transfer:

$$\frac{\partial w}{\partial \varphi}\cdot\frac{\partial \varphi}{\partial t} = \nabla\cdot(D_{\varphi}\nabla\varphi + \delta_p\nabla(\varphi\ p_{sat})) \qquad (1)$$

Energy transfer:

$$\frac{\partial H}{\partial T}\cdot\frac{\partial T}{\partial t} = \nabla\cdot(\lambda\ \nabla T) + h_v\nabla\cdot(\delta_p\nabla(\varphi\ p_{sat})) \qquad (2)$$

where φ is the relative humidity (-), t is time (s), T is temperature (K), c is specific heat (J/(kg·K)), w is moisture content (kg/m^3), p_{sat} is vapour pressure at saturation (Pa), λ is thermal conductivity (W/(m·K)), H is total enthalpy (J/m^3), D_φ is liquid conduction coefficient (kg/(m·s)), δ_p is vapour permeability (kg/(m·s·Pa)), h_v is latent heat of phase change (J/kg).

Heat and moisture convection is not calculated. The air flow is calculated in a simplified way, as air change between studied layer and indoor/outdoor air.

In the simulation program it is possible to describe the air flow inside the material layers. The air flow can be added as the air change rate. The air in material layer is mixed with outdoor air or indoor air. In studied cases the new material layers added inside the room are more air tight than the existing log layer and external cladding. So the air inside the wall is mixed with the outdoor air.

2.2 Material properties

WUFI contains a large material database from different sources. In addition to basic constant data (bulk density, porosity, specific heat capacity of dry material, thermal conductivity of dry material, water vapour diffusion resistance factor of dry material) WUFI database includes also some moisture-dependent properties: moisture storage function w (kg/m^3), liquid transport coefficient for suction D_{ws} and for redistribution D_{ww} (m^2/s), thermal conductivity λ (W/(m·K)) and vapour diffusion resistance factor μ (-).

The liquid transport coefficient for suction D_{ws} describes the capillary uptake of water when the imbibing surface is fully wetted. The liquid transport coefficient for redistribution D_{ww} describes the speed of distribution of imbibed water when wetting is finished. As soon as the water is removed from the suction surface, the field of capillary pressures changes to a new equilibrium. Redistribution is dominated by the smaller capillaries since their higher capillary tension draws the water out of the larger capillaries. Since redistribution is a slower process than suction, the moisture diffusivity for redistribution generally is markedly lower than moisture diffusivity. Depending on the material, this redistribution can be 3 to 20 times slower than absorption, typically about one tenth (Krus 1996, Künzel 2000).

To get a better understanding about the relationship between material properties and diffusive and capillary moisture flow in the wall. Four different cases were calculated.

The influence of the material properties to the total moisture flow is presented in Fig. 2

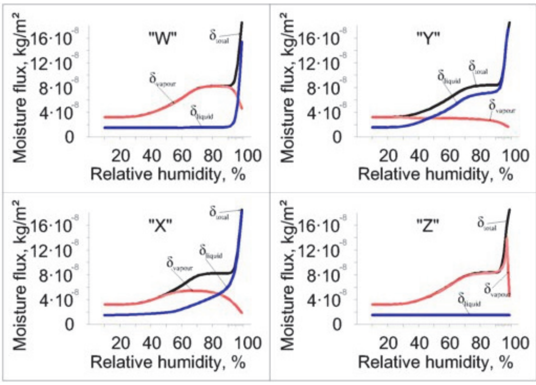


Fig. 2 Total moisture flux in the middle of the material in different cases of μ and D_{ws}.

In the first case, case "W", the material properties were used as described in the material database, both moisture-dependent. In the next to cases, "X" and "Y", the water vapour diffusion resistance factor was set as constant, In the last case, "Z", the simulation was done excluding capillary flow. In different cases the moisture flow through the log layer was described by the vapour diffusion resistance factor and capillary flow according to the cases shown in Fig. 2.

Because the measurement results showed high humidity level inside the wall during the whole measurement period there exists in addition to water vapour flow also the water flow in liquid form. Therefore material properties should be described considering both moisture flows: vapour diffusion and liquid transport. Both properties depend on moisture content of the material.

Material properties affecting the speed of liquid moisture transport are liquid transfer coefficients. The effect of capillary flow may have a significant impact on the simulation results depending on the materials. In case the material properties were used as described in the material database, both moisture-dependent, the capillary flow starts to have an impact on moisture flux on higher RH levels than 95%. The results of simulation tests on external walls with capillary flow are presented by Vinha 2007. If vapour resistance change significantly already in the hygroscopic range the capillary flow was set to start affecting the materials when the value of water resistance started to diminish (Vinha 2007).

The liquid transfer coefficient of the library material was compared with the moisture diffusivity values presented in the literature. The results of different tests and the variability of the values isare presented by Time 1998, Kumaran 1996, 2002, Krus 1999, Sonderegger 2011. The comparison between the moisture diffusivity of the library material data and results presented in the literature show the difference of about two orders of magnitude. The material properties of the wood layer in the simulation model was changed according to the difference, the liquid transport coefficient for suction and the liquid transport coefficient for redistribution were multiplied by 100. The modified materials were used to describe the log layer of the walls.

The simulations were done using modified material. The properties of different materials used in simulation models are presented in Table 1.

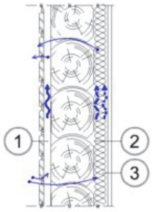
Table 1 Material hygric properties in simulation models.

	RH [%]	Gypsum board	Mineral wool	Cellulose wadding	Reed insul. Mat	Wood (spruce)	Air barrier
Bulk density ρ [kg/m³]		574	60	60	135,8	390	130
Porosity ξ [m³/m³]		0,77	0.95	0,95	0,9	0,75	0,001
Water vapour diff. resistance factor μ [-]		6,9	1,3	1,5	2	108*	100
Thermal conductivity λ [W/(m·K)]		0,19	0,045	0,06	0,065	0,13	-
Moisture storage function w [RH / (kg/m³)]	33	2,4		3,4	5,2	27,3	
	55	5,1	-	4,9	6,3	37,1	-
	97	7,2		24,6	36,2	81,9	
	100	17,7		570	600	600	
Liquid Transport D_{ws} [RH / (m²/s)]	33	$2,9\cdot10^{-12}$		$7,5\cdot10^{-12}$	$6,2\cdot10^{-11}$	$4,4\cdot10^{-11}$	
	55	$1,5\cdot10^{-11}$	-	$1,4\cdot10^{-11}$	$8,1\cdot10^{-11}$	$5,9\cdot10^{-11}$	-
	97	$2,2\cdot10^{-10}$		$2,2\cdot10^{-10}$	$9,7\cdot10^{-10}$	$1,3\cdot10^{-10}$	
	100	$1,6\cdot10^{-7}$		$4,9\cdot10^{-8}$	$5,2\cdot10^{-8}$	$9,2\cdot10^{-10}$	
Liquid Transport D_{ww} [RH / (m²/s)]	33	$2,9\cdot10^{-13}$		$7,5\cdot10^{-13}$	$6,2\cdot10^{-12}$	$4,4\cdot10^{-11}$	
	55	$1,5\cdot10^{-12}$		$1,4\cdot10^{-12}$	$8,1\cdot10^{-12}$	$5,9\cdot10^{-11}$	
	97	$2,2\cdot10^{-11}$	-	$2,2\cdot10^{-11}$	$9,7\cdot10^{-11}$	$1,3\cdot10^{-10}$	-
	100	$1,6\cdot10^{-8}$		$4,9\cdot10^{-9}$	$5,2\cdot10^{-9}$	$9,2\cdot10^{-10}$	
*Wood (spruce) moisture dependent water vapour diff. resistance factor [RH / (μ)]				30	60	70	100
				108	39	27	27

2.3 Airflow in the wall

Assumption was made that moisture flow can be affected by convection. The convection can be caused by the temperature difference or by wind.

The convective flow was entered as the air change source in the material layers on both sides of the existing log layer. First rough estimation was done about the air change rate based on the studies made by Vinha 2007, Künzel 2011, Kehl 2011, Hägerstedt 2011. The final air change rates used in the simulation models were 2,5 1/h between the external cladding and the existing log layer, 2 1/h in side the 5 mm thick insulation layer, and 0,5 1/h in the rest of the insulation layer on the internal side of the log layer. Air change source described in the simulation model is shown in Fig. 3.



Position	Air change rate [1/h]
1 between external cladding and log layer	2,5
2 between insulation and log layer (5mm insulation layer)	2,0
3 inside insulation material (45mm insulation layer)	0,5

Fig. 3 Air change source in the material layers.

2.4 Boundary conditions

The outdoor and indoor temperature and RH was measured at one hour intervals inside the room and outside the wall. The results are shown in Fig. 4.

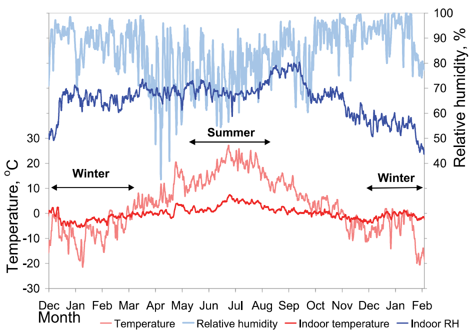


Fig. 4 The measured temperature and relative humidity.

Outdoor temperature varied between -21.5°C and +33.6°C and RH between 22% and 100%. During 2009-2010 winter average outdoor temperature was -7.4°C (min. -21.5°C, max. +4.2°C) and RH 89% (min. 62%, max. 100%). Indoor temperature varied between +13.5°C and +27.5°C and RH between 43% and 83%. During 2010-2011 winter average indoor temperature was +17.4°C (min. +13.5°C, max. +24.5°C) and RH 64% (min. 43%, max. 74%).

The dependence of the indoor temperature on the outdoor temperature is shown in Fig. 5. Indoor temperature depends quite linearly on the outdoor temperature. Indoor RH was high during the cold period consequently of low temperature and high humidity loads.

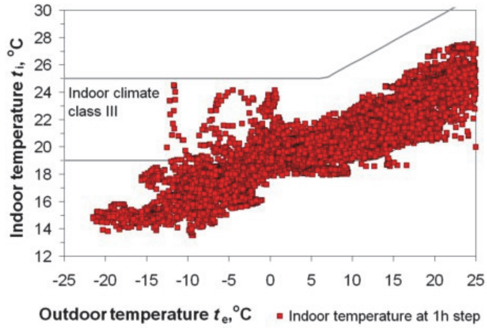


Fig. 5 The dependence of the indoor temperature on the outdoor temperature.

Humidity loads are presented as internal moisture excess that shows the difference between the indoor and outdoor air humidity by volume (potential for water vapour diffusion). Dependence of the moisture excess on the outdoor temperature is shown in Fig. 6. Black dotted line presents the 90 % critical level. During cold periods the weekly average internal moisture excess was +7 g/m^3.

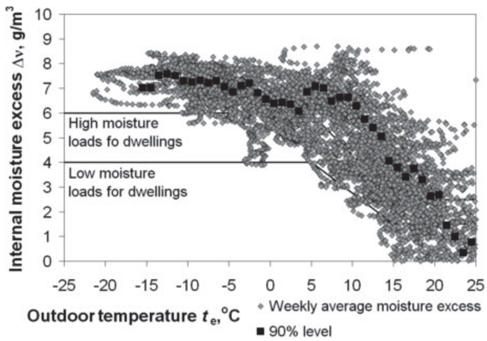


Fig. 6 The dependence of the moisture excess on the outdoor temperature.

The boundary conditions of the external and internal surface of the wall were calculated using temperature and RH measurement results to eliminate the effect of surface transfer coefficients. The internal surface RH was calculated by changing the water vapour pressure at saturation according to the measured temperature on the surface of the wall.

3. Results

3.1 Influence of definition of material properties and airflow

Two potentials for moisture flow are introduced in the program. The liquid transport flux depends on relative humidity and the water vapour diffusion flux depends on vapour pressure in a porous hygroscopic building material. There is an interaction between water vapour diffusion and liquid transport in building components (Künzel 1995). Depending on the gradients of vapour pressure and relative humidity the moisture flow can run in same or in opposite directions. For example in cold climate under winter conditions the vapour pressure is higher inside than on the outside of the building due to the temperature difference.

The vapour diffusion takes place from the inside to the outside. Usually the relative humidity is higher outside than inside thus the gradient of relative humidity runs the water content opposite direction.

The phenomenon described introduces some error into calculations if the material properties are described only using water vapour diffusion resistance factor or moisture diffusivity in the simulation model.

In the studied walls the hygrothermal properties of wood play important role, because log layer is geometrically dominating material.

In different cases the moisture flow through the log layer was described by the vapour diffusion resistance factor and capillary flow according to the cases shown in Fig. 2. The results in case of mineral wool are shown in Fig. 7.

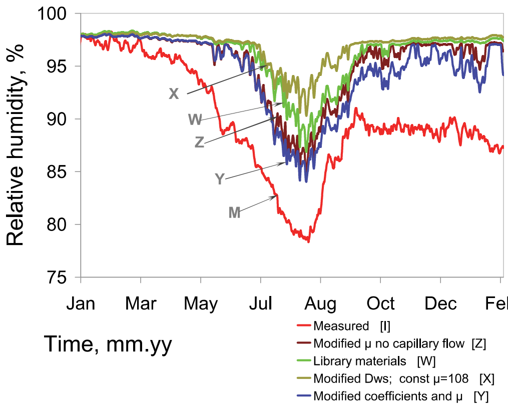


Fig. 7 Calculated relative humidity inside the wall A between the insulation (mineral wool) and log layer.

No convective air flow is considered in different simulation cases presented in Fig. 7.

In all cases the calculated relative humidity values were higher than the measured values. There was no good correlation between the measured and calculated results. In all cases the slope of drying and wetting follows the measured value line but drying starts later and lasts for a shorter time. Therefore the RH level stays higher than measured RH level.

The RH values after the wetting process are on the same level in case of the library materials and modified liquid transfer coefficients with constant vapour diffusion resistance factor equal to dry material. In comparison of the cases there is the difference between changes in the RH levels before the drying. The reason for that may be the speed of moisture transport. The closest results to the measured results are in case with the moisture dependent vapour diffusion resistance factor and with increased liquid transfer coefficients affecting in the hygroscopic range. By change of the liquid transport coefficients the proportion of the capillary flow was increased on the lower levels of RH.

The slope of drying and wetting follows the measured value line and drying starts later and lasts for a longer time than in case with out capillary flow. Therefore the simulations with changed liquid transport coefficients give better results.

Airflow inside the insulation layer influence moisture conditions of internally insulated log wall in a cold climate as shown by by Ojanen 2007.

Air tightness measurement showed air leakage rate of the building envelope q_{50}= 7,4 $m^3/(h \cdot m^2)$. Therefore in real life the air leakages exist through the log layer in the wall.

Additionally, the poor air tightness of the existing log layer favours the convective flow through gaps, cracks and holes inside the wall.

The air flow was added in the simulation model so the air inside the wall is mixed with the outdoor air. Air change source described in the simulation model is shown in Fig. 3.

The simulation results with the convection inside the wall are presented in Fig. 8.

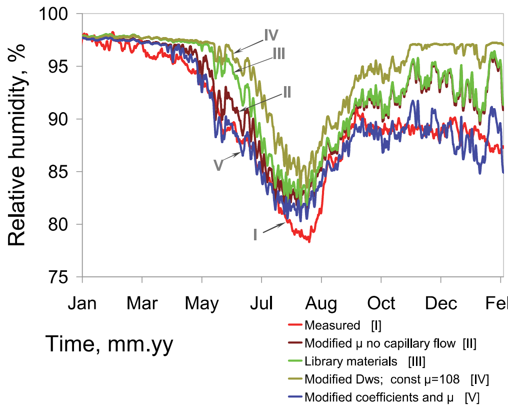


Fig. 8 Calculated relative humidity inside the wall A between the insulation (mineral wool) and log layer with the air change rates.

The added air flow lowered the RH level in side the wall between the insulation and log layer in all cases.

The final results show good correlation between the measured values and calculated values when the liquid transport coefficients start to affect in the hygroscopic range and the air flow is considered. During spring the drying and during autumn the wetting are well in line with the measured results. There is a good correlation between the drying and wetting period.

3.2 The wall descriptions and calculated results in different test wall assemblies.

The initial log wall construction consisting of a 140 mm log sealed with a tow and covered externally with sheathing paper and 20-mm wooden cladding was insulated from the interior using three different insulation materials: mineral wool, cellulose wadding and a reed insulation mat.

3.2.1 Walls A and B with mineral wool insulation

The comparison of calculated temperature and measured temperature showed very good agreement for wall A. Temperature and relative humidity levels in the wall between the log and mineral wool are presented in Fig. 9 and Fig. 10.

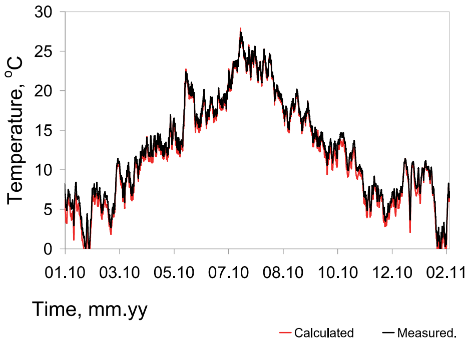


Fig. 9 Calculated temperature inside the wall A between the insulation (mineral wool) and log layer.

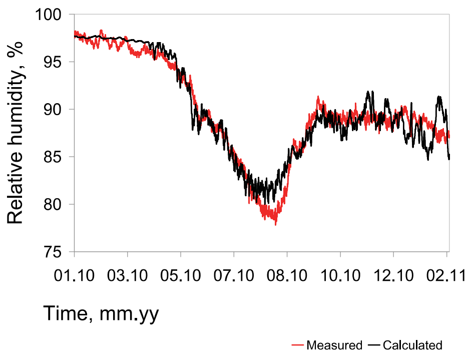


Fig. 10 Calculated relative humidity inside the wall A between the insulation (mineral wool) and log layer with changed transport coefficients.

3.2.2 *Walls C and D with cellulose wadding insulation*

Temperature and relative humidity levels in the wall between the log and cellulose wadding are presented in Fig. 11 and Fig. 12.

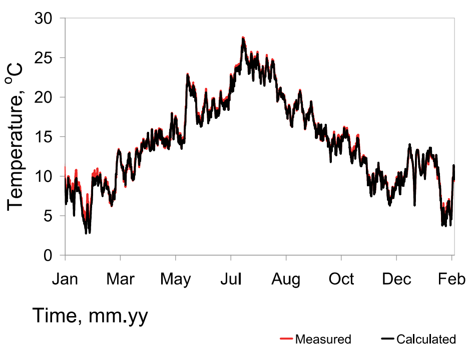


Fig. 11. Calculated temperature inside the wall C between the insulation (cellulose wadding) and log layer.

There is a good correlation between the measured temperature values and calculated temperature values.

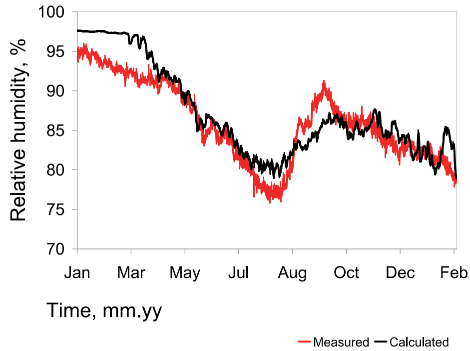


Fig. 12 Calculated relative humidity inside the wall C between the insulation (cellulose wadding) and log layer.

There is a difference in the beginning of the period.

3.2.3 *Walls E and F with reed insulation*

Temperature and relative humidity levels in the wall between the log and reed insulation mat are presented in Fig. 13 and Fig. 14.

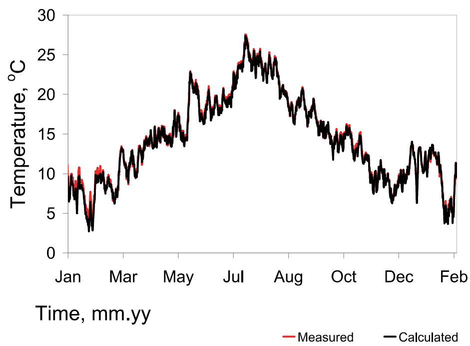


Fig. 13. Calculated temperature inside the wall E between the insulation (reed insulation mat) and log layer.

There is a good correlation between the measured temperature values and calculated temperature values.

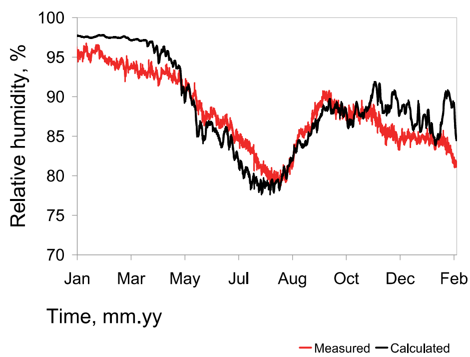


Fig. 14. Calculated relative humidity inside the wall between the insulation (reed insulation mat) and log layer.

4. Discussion

Including or excluding the capillary flow in the simulations affects the calculation results. Including the capillary flow in the simulation model improved the calculation results. Dividing the total moisture flow between diffusion and capillary flow may cause errors without knowing the exact properties of the material.

The first calculated RH values excluding the capillary flow were much higher than the measured RH levels inside the wall between the log layer and the insulation if the material properties from the programs database were used. Also in the case including the capillary flow RH levels were higher than measured values. After entering the air change rate into the simulation model the calculated RH levels were higher than the measured results. It is arguably better if the calculated results are higher than the measured values. It can be concluded that the calculated results show the riskiness of the internal insulation if the assessment of the hygrothermal performance of the retrofitting solution has to be done. The situation would be worse if the calculation results were smaller than the measured values. Then there would be a possibility of making a wrong decision on using internal insulation as the retrofitting solution.

The air change rate in the material layers was also noticed to have an effect on the calculation results. The air change rate was considered to be the moisture flow affecting factor connected to the air tightness of the existing log wall and was equal in simulation models with different insulation materials. The air change rate was introduced as a constant during the whole calculation period. This can cause an error because in real life it is not constant due to the variable temperature gradient and wind.

The quality of the simulation results depends on the input variables, on the assumptions and simplifications made and on simulation settings. Hygrothermal performance simulations using HAM-simulation programs may contain different kinds of errors beginning with the description of the existing wall assemblies to the chosen material properties in the case of retrofitted building constructions.

No laboratory tests were conducted to obtain the data about the properties of the different building materials used in the existing wall construction. The material database of the simulation tool and material data from the literature was used. The hygrothermal properties of the building materials not described in the material database were entered into the program based on the results from the literature.

The hygrothermal properties of different species of wood vary considerably. Properties may also vary because of the age of the wood and history of the climate conditions the wood has been exposed to. There is a need of information about the possible changes in material properties during the ageing. To get more reliable calculation results the material properties should be determined by laboratory tests.

5. Conclusion

The simulation models of six internally insulated log walls were validated using long-term field measurements. The WUFI was selected for the hygrothermal performance simulations.

A good correlation between the calculated results and measured values was achieved after the modification of the material properties and adding a factor as air change rate in the material layers inside the wall. Drying and wetting are determined more accurately if the convective air flow is included in the hygrothermal simulation model.

The quality of the results depends on the input variables, on the assumptions and simplifications made and on simulation settings.

In cases of retrofitting, the properties of building materials used in existing wall constructions should be determined by laboratory tests, if possible, to get more reliable calculation results.

The validated model will be used in further studies to make analysis of the performance of the internally insulated log wall in cold climates.

6. Acknowledgements

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