THESIS ON CIVIL ENGINEERING F65

Renovation and Energy Performance Improvement of Estonian Wooden Rural Houses

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TTÜ
PRESS

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Eesti puidust maaelamute renoveerimine ja energiatõhususe parandamine

ÜLLAR ALEV

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ABSTRACT

Wooden detached houses represent the majority of buildings in rural areas in Estonia. The design service life of these rural wooden building is nearing its end. Renovation alternatives to improve energy performance of historic rural houses in Estonia (cold climate) are analysed. The study was conducted by a combination of field measurements and simulations. The indoor climate, current condition of structures, air leakage rate and need for renovation were determined by field measurements in 51 traditional rural houses. Interior thermal insulation in a cold climate is risky from a hygrothermal point of view. To avoid mould growth in wall structures the main parameters influencing the hygrothermal performance of interiorly insulated walls were varied in the calculation model and mould growth risk was identified. Based on field measurements, energy simulation models were validated and used to calculate energy use for different renovation measures. Energy renovation packages were calculated for different scenarios.

Detailed information is given about building envelope elements and possible variants. All possible damage detected during the survey of 51 houses in Estonia is described and illustrated with drawings and photographs. Most often, rot damage was found in foundation wall and log wall joints, caused mainly by broken or missing rain protection or waterproofing of the edge of the foundation.

The indoor climate in all the investigated historic rural houses needs improvement. The room temperature was mainly too low during winter. During the winter period, the design value of moisture excess was 4–5 g/m^3 and the average moisture load was 2.5–3.5 g/m^3. The indoor humidity load in historic houses was similar to that in modern houses. Inhabitants rated the overall indoor climate as healthy.

At the pressure difference of 50 Pa the mean air leakage rate was 15 m^3/(h·m^2) and the mean air change rate was 21 h^{-1} in the database. The internal finishing of the wall with plywood or plaster played a significant role in the condition of the air leakage of the building envelope. The typical air leakage places were doors and windows, external wall and ceiling joints, external wall and floor joints and cracks between logs.

The interior insulation layer must be covered with a vapour barrier; its equivalent vapour diffusion thickness of 2 m or more is acceptable when the indoor moisture excess is up to 5 g/m^3 during winter. In these conditions, the maximum measured moisture content of logs before insulation should be below 12% and the thickness of interior insulation of mineral wool can be up to 50 mm. It is necessary to carefully install a vapour barrier covering interior insulation to avoid air leakages through it.

It is shown that the improvement of building service systems and the energy source holds the largest energy saving potential. The building envelope of old rural houses needs improvement also due to high thermal transmittance and air leakage. The insulation of the external wall has the largest single energy saving potential of the building's envelope. The results show how energy savings depend on energy saving targets, thermal transmittance of original structures and building service systems.

Keywords: renovation of wooden detached house, indoor climate, energy efficiency, interior thermal insulation, hygrothermal performance, air leakage of external envelope.

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KOKKUVÕTE

Puidust eramud moodustavad enamuse Eesti maapiirkonna hoonetest. Nende puidust eramute eluiga on lähenemas lõpule. Analüüsitud on renoveerimislahendusi vanade maamajade energiatõhususe parandamiseks Eesti külmas kliimas. Uuringud põhinevad nii välimõõtmiste ja kui näidisobjektide modelleerimise tulemustel. Välimõõtmistega 51 traditsioonilises maaeramus selgitati välja sisekliima näitajad, konstruktsioonide hetkeolukord, välispiirete õhupidavus ja üldine renoveerimisvajadus. Külmas kliimas on seespoolne lisasoojustamine niiskustehniliselt riskantne lahendus. Hallituse arengu vältimiseks seinakonstruktsioonides varieeriti arvutusmudelis peamisi seespoolse lisasoojustamise niiskustehnilist toimivust mõjutavaid parameetreid ja arvutati hallituse kasvu tõenäosus. Tuginedes välimõõtmistele valideeriti energiasimulatsioonide mudelid ja arvutati nende abil erinevate renoveerimismeetmetega saavutatava energiakasutuse standardtingimustel. Energia-renoveerimise meetmete paketid arvutati vastavalt erinevatele soovitud eesmärkidele.

Eramute piirdekonstruktsioonide elemendid on detailselt kirjeldatud koos võimalike variatsioonidega. Kõik vaatlusega avastatud kahjustused 51 Eesti elamus on kirjeldatud ja illustreeritud piltide ja joonistega. Kõige sagedamini leiti mädaniku kahjustusi vundamendi ja palkseina liitekohas, peamiseks põhjuseks oli katkine või puuduv veelaud või muu vihmakaitse vundamendi välisserva kohal.

Sisekliima kõigis uuritud vanades maaeramutes vajab parendamist. Talveperioodil oli sisetemperatuur tavaliselt liiga madal. Talveperioodi niiskuslisa arvutusväärtus oli $4 - 5$ g/m^3 ja keskmine niiskuslisa oli $2.5 - 3.5$ g/m^3. Eluruumide niiskuskoormus oli vanades eramutes sarnane kaasaegsete elamutega. Elanikud hindasid vanade maaeramute sisekliimat tervikuna tervislikuks.

Eramute keskmine õhulekkearv 50 Pa suuruse rõhuerinevuse juures oli 15 m^3/(h·m^2). Vastav keskmine ruumi õhuvahetuskordsus 50 Pa suuruse rõhuerinevuse juures oli 21 korda tunnis. Leiti, et seest poolt krohvitud või vineeriga kaetud välissein vähendab oluliselt hoone välispiirete õhuleket. Tavalised õhulekkekohad uuritud eramutes olid järgmised: aknad ja uksed, välisseina ja lae liitekoht, välisseina ja põranda liitekoht ning praod palkide vahel.

Seespoolse lisasoojustuse kiht peab olema kaetud aurutõkkekihiga, mille suhteline difusioonitakistus on 2 m või rohkem, kui seejuures niiskuslisa talveperioodil on kuni 5 g/m^3. Mainitud tingimustel võib maksimaalne mõõdetud seinapalkide niiskus enne soojustamist olla kuni 12% ja seespoolse mineraalvillast lisasoojustuse kihi paksus kuni 50 mm. Seespoolne lisasoojustus tuleb katta hoolikalt paigaldatud aurutõkkekihiga vältides õhulekkeid läbi selle.

Suurimat energiasäästu potentsiaali omab eramu tehnosüsteemide ja energiaallika parendamine. Vanade maamajade piirdekonstruktsioonid vajavad parendamist ka suure soojusläbivuse ja õhulekete vähendamiseks. Piirdekonstruktsiooni renoveerimismeetmetest suurima energiasäästu potentsiaaliga on välisseinte lisasoojustamine. Tulemused näitavad kuidas energiasääst sõltub säästu eesmärgist, algsete eramu piirdekonstruktsioonide soojusläbivusest ja eramu tehnosüsteemidest.

Märksõnad: palkeramu renoveerimine, sisekliima, energiatõhusus, seespoolne soojustus, niiskusturvalisus, välispiirete õhuleke.

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Üllar Alev

April 2017

CONTENTS

LIST OF PUBLICATIONS

This thesis is based mainly on data presented in the following publications in peer-reviewed journals:

I Alev, Ü. and Kalamees, T. (2016) ‘Evaluation of a technical survey and the renovation needs of old rural wooden houses in Estonia’, *Journal of Building Survey, Appraisal & Valuation*. Henry Stewart Publications, 5(3), pp. 275–290.

II Alev, Ü., Kalamees, T., Eskola, L., Arumägi, E., Jokisalo, J., Donarelli, A., Siren, K. and Broström, T. (2016) ‘Indoor hygrothermal condition and user satisfaction in naturally ventilated historic houses in temperate humid continental climate around the Baltic Sea’, *Architectural Science Review*, 59(1), pp. 53–67. doi: 10.1080/00038628.2015.1038980.

III Alev, Ü. and Kalamees, T. (2016) ‘Avoiding mould growth in an interiorly insulated log wall’, *Building and Environment*, 105, pp. 104–115. doi: 10.1016/j.buildenv.2016.05.020.

IV Alev, Ü., Uus, A. and Kalamees, T. (2015) ‘Comparison of mineral wool, cellulose and reed mat for interior thermal insulation of log walls’, *Journal of Civil Engineering and Architecture Research*, 2(9), pp. 938–947.

V Alev, Ü., Eskola, L., Arumägi, E., Jokisalo, J., Donarelli, A., Siren, K., Broström, T. and Kalamees, T. (2014) ‘Renovation alternatives to improve energy performance of historic rural houses in the Baltic Sea region’, *Energy and Buildings*, 77, pp. 58–66. doi: 10.1016/j.enbuild.2014.03.049.

And on the following peer-reviewed conference publication:

VI Alev, Ü. and Kalamees, T. (2013) ‘Field study of airtightness of traditional rural houses in Estonia’, in *Proceedings of CLIMA 2013*. Prague, id. 780.

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.

The field investigations presented in article I were conducted and the article was written by the author. The results were discussed with the co-author.

In II, most of the fieldwork in Estonian houses and analysis of the data from three counties with main conclusions were made by the author (Estonian results are presented in this thesis). The research principles of the study were developed in cooperation with T. Kalamees. Fieldwork in the other two countries was made by the co-authors. The literature overview and discussion about results were written together with the co-authors.

In III, research principles of the study were developed, the test wall was built and measurements were gathered by the co-author. The analysis of the measured data and the simulations were carried out and conclusions were drawn by the author. Results were discussed with the co-author and the literature overview was written together with the co-author.

In IV, the research principles of the study were developed together with T. Kalamees. A. Uus built the test house. All authors were involved in making the measurements. Calculations were made in cooperation with A. Uus and the paper was written by the author.

In V, most of the fieldwork in Estonian houses and data analysis of Estonian data were made by the author (Estonian results are presented in this thesis). The research principles of the study were developed together with the co-authors. The fieldwork in the other two countries was made by the co-authors. The paper was composed by the author; the literature overview and discussion about results were written together with the co-authors.

In VI, the measurement methods were developed together with T. Kalamees. The paper was written by the author based on field measurements mainly made by the author. Results were discussed with the co-author.

1 INTRODUCTION

1.1 Background

The existing buildings are one of the greatest wealth of society. The detached house is the second largest building type after the apartment building in Estonia. In Estonia detached houses represent 40% of the residential buildings in terms of floor area and 72% in terms of numbers. Although wooden detached houses have been built both in rural areas and in towns, in rural areas they were preferred as a simpler and cheaper construction type than stone buildings popular in central areas of towns due to fire-safety issues. Typical Estonian rural dwellings were mainly built in the 20th century. Often these old rural log houses are still in use: as main homes or summer cottages. Figure 1.1 shows that the majority (55% of closed net area and 67% based on the number together with timber frame houses) of the detached houses built before 1970 have a wooden construction (Majandus- ja Kommunikatsiooniministeerium, 2010). Before World War II, log walls were the primary wall construction type, with the wooden frame construction becoming more widespread later. Log houses of different sizes were common in the Baltic and Nordic countries a century ago. Often these old log houses are still in use. Today log houses are gaining popularity again because of the natural building material and low embodied energy, and they are still a usable building type. Based on the database of Estonian historic rural barn-dwellings, the renovation and reuse of old traditional historic rural houses has become more widespread during the recent decade (Muinsuskaitseamet, 2016).

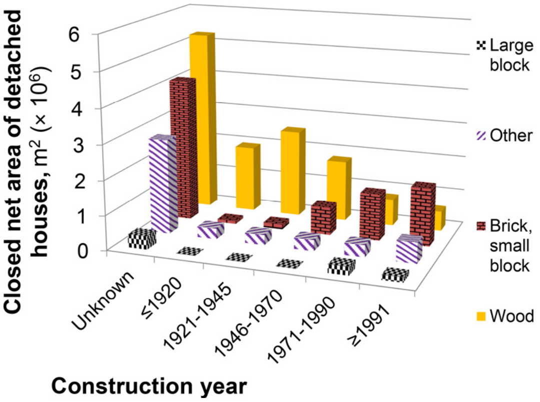


Figure 1.1. Floor area of detached houses in Estonia as broken down by load-bearing structure material and construction year.

In the course of time, the use of historic and traditional rural houses has changed. Today people have different requirements for thermal comfort, function and energy performance of homes. Therefore, the owners of old traditional houses have an ambition to renovate their homes according to these requirements. Also, the visual architectural look of a house plays a role when its new owners want to remove the old cheap covering materials like asbestos cement board on the roof and renovate the house into a stylish old-looking barn dwelling. In the case of cultural-historic and milieu valuable buildings, special attention should be paid to the preservation of cultural heritage. Therefore, selected technical solutions should be as suited as possible for the traditional houses and landscape.

Age is commonly considered the determining factor not only in the deterioration process but also in the overall performance of a building (Balaras et al., 2005). About 71% of the rural houses are over 50 years old, and about 59% are more than 70 years old (Majandus- ja Kommunikatsiooniministeerium, 2010). Typically the design service life is 50 years. Service life is the ‘Period of time after manufacturing or installation during which all essential properties meet or exceed minimum acceptable values, when routinely maintained’ (Masters, 1986). As design service life is over for most wooden rural detached houses, it is necessary to develop a strategy to extend their service life and improve their current technical condition. Other reasons for renovation may include giving a new function to rooms, relocating/removing internal walls to modify internal space, preserving an old style, energy efficiency (V), indoor climate and user satisfaction (II) etc.

A correct understanding of the current technical condition and the reasons for potential damage to a house is needed to estimate the cost and time required for any major renovation works. Improving the visual appearance of the house is only a minor reason for undertaking such renovation. Most common major renovation works include replacing old service systems or energy sources with more efficient ones in a house and/or improving the thermal performance of the external envelope of a house (V). Additionally, the modern approach of renewable energies is a potential option.

1.2 Objective and content of the study

The aim of this study is to analyse the renovation solutions fulfilling inhabitants’ ambition to decrease the energy use and improve the indoor climate in their wooden rural houses. To provide desired renovation solutions to house owners considering the condition of building structures, indoor climate conditions, performance of the building envelope and energy savings, the following specific tasks were formulated:

- description of different construction types with main damage found to determine the urgent renovation needs;
- measuring of existing indoor climate conditions and hygrothermal loads in houses for the following analysis of hygrothermal performance of the interior thermal insulation;
- measuring of the airtightness and infiltration rate of the existing building envelope for subsequent energy performance calculations;

- comparison of thermal insulation materials used for interior insulation of log walls and working out solutions for interior thermal insulation for wooden rural houses;
- development of renovation measures to improve the energy performance and indoor climate of wooden rural houses.

The thesis is based on five peer-reviewed journal articles and one conference paper (see List of publications).

The description of materials and constructions used in the rural log houses in Estonia as well as their technical conditions is given in article I. Multiple versions of construction types are provided. Damage found in the houses examined is described, including their probable causes.

Data on the indoor temperature, humidity load and user satisfaction in naturally ventilated rural houses are given in article II. Knowledge about indoor climate conditions is necessary for developing policy and practical solutions regarding sustainable renovation and design of energy efficiency, indoor climate and hygrothermal performance of historic and traditional rural houses.

Field measurements of the airtightness and thermography have been carried out in 48 traditional rural houses in Estonia. Passive tracer gas measurements have been carried out twice (during summer and winter) in 11 houses from the previous measurement selection. The measurement results are given and analysed in article VI. The air leakage rate value and the distribution of leakage places are important input data for energy calculations.

The insulation of the external wall has the largest single energy saving potential concerning the building's envelope according to results presented in article V. The common external wall insulation solution to insulate the original wall from the external side is hygrothermally safe. Some house owners who want to expose the external surface of the log wall or are not allowed to cover it with an additional insulation layer prefer to use interior insulation. As the interior insulation is not as hygrothermally safe as the external insulation layer, designers and customers are looking for interior insulation solutions that provide moisture safe design. In paper IV three insulation materials (cellulose fibre, reed mat and mineral wool) are compared and limitations for log wall insulation identified by varying structural and indoor climate parameters are presented. In paper III hygrothermally functioning combinations are identified by varying the main parameters affecting the hygrothermal performance of an interiorly insulated log wall. Correct insulation solutions for designers and owners of log houses are suggested to improve the energy efficiency and thermal comfort of these houses.

To find out the energy saving potential of the rural house a model was composed and validated with a sample house. Article V presents the results of energy saving when only one energy renovation measure was applied. The analysis showed that the improvement of building service systems and the energy source has the greatest energy saving potential. The building envelope of old rural houses needs improvement also due to its high thermal transmittance and air leakage. Renovation packages were composed of single energy renovation measures for different scenarios in article V (minimal influence on the appearance of the house, improvement of thermal comfort, modernisation of building service systems) for achieving different energy saving levels.

The main points of newly acquired knowledge about historic rural wooden houses discussed in this thesis are as follows:

- The indoor climate measurements showed that the indoor temperature in rural houses was generally low. Nevertheless, inhabitants have adapted to it and rate the overall indoor climate as healthy. In periodically used rural wooden houses the moisture excess may be of the same level as in continuously used detached houses despite the periodic use and the leaky building envelope.
- The use of the house influences significantly the natural air infiltration rate: it is three times lower in unused houses compared to permanently used houses when the air leakage rate of the houses is similar. The most significant factor affecting the airtightness of the house is the internal covering of the external walls.
- The hygrothermal performance of interior insulation is most strongly influenced by the water vapour resistance of the vapour barrier followed by the indoor moisture load, which is given lower importance as it cannot be decided by the designer. The third factor is thermal transmittance of the additional interior insulation layer. The initial moisture content of logs, which comes fourth, has similar influence but is only measurable and cannot be defined by the designer. The thickness of logs and indoor temperature level have the lowest influence on the hygrothermal performance of log walls.
- A database of the current state of historic rural wooden houses in Estonia has been composed and scientifically proved guidelines are presented for extending the lifetime of these houses and adjusting them for modern use.
- The largest energy saving in Estonian wooden rural houses can be achieved with the improvement of building service systems and the energy source or by adding insulation to the external wall as the best single structural energy saving measure.

The results of this thesis have also practical application:

- Energy auditors and engineers can use indoor climate and airtightness measurement results as input data in hygrothermal or energy simulations.
- Information about airtightness of the building envelope is used in developing energy performance legislation in Estonia.

- The renovation measures derived from measurements shown in this thesis have been presented in seminars arranged for owners of old rural houses and separate seminars for architects and builders of rural houses.
- The overview of constructions and their damage can be used as educational information for students studying renovation topics.
- The results of the study of interior insulation can be used as reference by specialists designing specific interior insulation cases. Reduction of energy use by applying specific renovation measures can be the first input for homeowners and architects when making renovation plans and economic analysis.

The thesis is compiled so that it can be understood without the papers included as the appendixes. The results, discussion and conclusion chapters include all the information, figures and tables relevant to Estonian houses treated in the papers. In the introduction of this thesis only a brief overview of full papers is given. The purpose of the methods chapter of this thesis is to give the reader a general understanding how the results were obtained; a detailed description of methods of each topic is given in full papers.

1.3 Limitations of the work

In the current thesis, only log detached houses are covered. Rural detached houses made of stone were less common before World War II and timber frame houses began to gain popularity later. Therefore timber frame, natural stone, brick and block houses are not discussed in this thesis.

The inspection of rural houses focused on load-bearing and building envelope structures such as walls, floors, roofs, foundations, windows and doors. This means that building service systems are not addressed. The stability of the load bearing structure has to be ensured and fire safety issues should be solved before considering energy renovation solutions or indoor climate improvements. Therefore it is assumed in this study that the structure of the house is stable, the roof is waterproof, there is no fire risk and all service systems work correctly.

Sakhare & Ralegaonkar (2014) concluded that the most important parameters to achieve a comfortable indoor environment are temperature and acoustic, visual and air quality. In this study, visual parameters were left out because the covering layers (paint or wallpaper) are easy to replace and their influence on the energy efficiency or indoor climate of the house is negligible. Temperature and humidity conditions were measured and other parameters were covered in a questionnaire. The inhabitants did not report any acoustic problems and therefore these measurements were not needed.

Exterior insulation is always a preferred solution in regions with cold climate if possible, because it is hydrothermally considerably safer than interior insulation. Different exterior insulation systems are widely used and therefore the effectivity and hygrothermal safety issues have been verified in practice over a long period in a number of houses. Many local handbooks giving tested external thermal insulation solutions exist and therefore these solutions are not discussed in this thesis. Highly insulated wooden frame walls pose hygrothermal risks in some variations; these were evaluated by Pihelo & Kalamees (2016).

Only mineral wool, cellulose fibre and reed were tested and compared as suitable interior insulation materials for log walls. It is not practical or economically reasonable to install (or test) many other insulation materials commonly used for insulating masonry walls because installation methods and hygrothermal properties of these materials are completely different. Mineral wool is used as representative of general insulation materials in the current thesis.

1.4 Nomenclature

1.4.1 Abbreviations

AAHP	Air−air heat pump
ACH	Air change rate in room
AF220	Attic floor with additional thermal insulation +220 mm
AF420	Attic floor with additional thermal insulation +420 mm
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
AT30	Improvement of airtightness of envelope by 30%
AT60	Improvement of airtightness of envelope by 60%
AWHP	Air−water heat pump
BC	Base case
BF200	Additional thermal insulation for base floor +100 mm
BF300	Additional thermal insulation for base floor +200 mm
DHW	Domestic hot water
ER	Electrical radiators
EU	European Union
EU27	European Union of 27 member states
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
EW220	External wall with additional thermal insulation +220 mm
GSHP	Ground source heat pump
HR0	Mechanical ventilation system without heat recovery
HVAC	Heating, ventilation and air conditioning
ICC	Indoor climate category
MS	Material study
OB	Oil condensate boiler
PS	Parametric study
PV	Photovoltaic panels
RC	Reference case
SC	Solar collectors for DHW
VHR60	Supply-exhaust ventilation with heat recovery 60%
VHR80	Supply-exhaust ventilation with heat recovery 80%
W0.8	New window with $U = 0.8$ W/(m^2·K)
W1.1	New window with $U = 1.1$ W/(m^2·K)
W1.6	Renovated window with $U = 1.6$ W/(m^2·K)
WB	Wood burning boiler
WS	New or renovated wood burning stove
WPB	Wood-pellet boiler

WUFI	Hygrothermal simulation program for the heat and moisture transfer in building envelope constructions

1.4.2 Symbols

DE	Delivered energy consumption, kWh/(m^2·a)
G	Moisture production indoors, g/h
M	Mould growth index, −
MC	Moisture content, %
$Mtoe$	Million tonnes of oil equivalent (≈ 42 gigajoules or 11,630 kilowatt hours)
n	Air change per hour, h^{-1}
n_{inf}	Calculated infiltration rate, h^{-1}
n_{50}	Air change rate in building at 50 Pa air pressure difference, m^3/(h·m^3) = h^{-1}
p	Statistical significance according to Student’s t-test
q_{50}	Air leakage rate of building envelope at 50 Pa air pressure difference, m^3/(h·m^2)
q_v	Ventilation airflow, m^3/h
PE	Primary energy consumption, kWh/(m^2·a)
RH	Relative humidity, %
S_{d}	Equivalent vapour diffusion thickness, m
T	Temperature, K
t	Temperature, °C
U	Thermal transmittance, W/(m^2·K)
w	Moisture content by mass, %
x	Product of several correction factors, −
λ	Thermal conductivity, W/(m·K)
μ	Water vapour diffusion resistance factor, −
ν	Humidity by volume, g/m^3
$\Delta\nu$	Moisture excess (difference between indoor and outdoor air water vapour content), g/m^3

1.4.3 Subscripts

$_{\mathrm{e}}$	External, outdoor
$_{\mathrm{i}}$	Internal, indoor
$_{\mathrm{s}}$	Surface
$_{\mathrm{d}}$	Diffusion

2 ENERGY PERFORMANCE AND INDOOR CLIMATE OF RURAL HOUSES

The journal articles in the appendix of the thesis present more detailed literature overviews about energy efficiency (VI), indoor climate (II), airtightness of houses (VI) and performance of interior insulation solutions (IV, V).

2.1 Estonian rural houses

The predominant historic rural house in Estonia is the barn-dwelling. The poly-functional barn-dwelling (Figure 2.1 A and B) served both as a living and a husbandry building. It consists of three main parts end to end: a kiln-room, a threshing room and bedrooms (Tihase, 2007). The kiln-room served as a living and working room all year round, although in autumn grain was dried there. Over the time improvements have been made to better adapt these buildings to people's needs. At the turn of the 18th and 19th centuries the need to build chimneys in dwellings in order to get rid of smoke was considered most urgent (Tihase, 2007). The barn-dwelling was far from comfortable and cosy for people. However, the barn-dwelling met the general needs of life although it included many shortcomings from today's point of view. External walls of the kiln-room and bedrooms are made of logs with a thickness of 0.12–0.20 m.

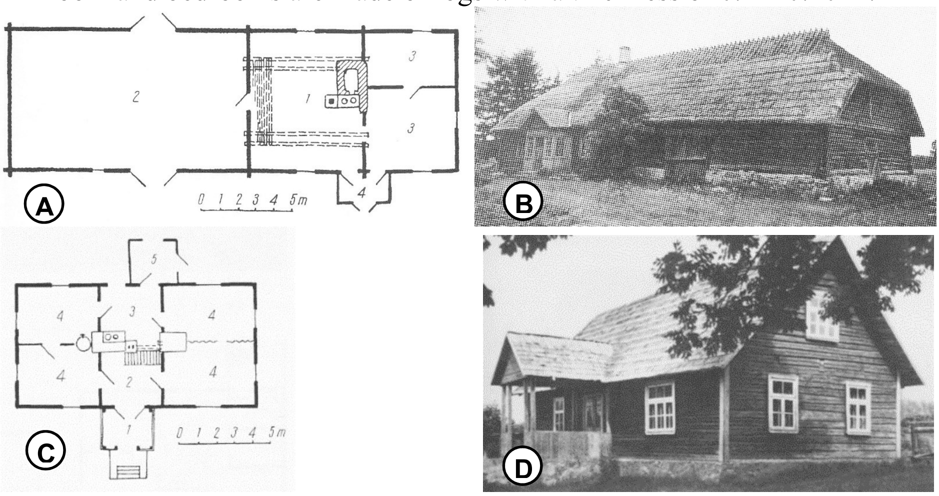


Figure 2.1. Ground plan of a barn-dwelling built in 1915−1916, Western Estonia: 1 – kiln-room; 2 – threshing-floor; 3 – living rooms; 4 – entrance hall (A). Photo of a barn-dwelling, Northern Estonia (B). View (D) and ground plan (C) of a dwelling, Southern Estonia: 1 – porch; 2 – entrance hall; 3 – kitchen; 4 – living rooms; 5 – veranda (Tihase, 2007).

Building of dwellings without the animal husbandry function began in the last decades of the 19th century (Figure 2.1 C and D). The ground plan of the dwelling house was similar to the living part of previous barn-dwellings, but if a barn house was built, it was a separate building away from the dwelling house.

In the first quarter of the 20th century more stylish houses with a mansard floor and verandas began to be built with up-to-date building materials and architectural lines used. All the houses were mainly heated with wood-burning stoves. Typically, there was only passive stack ventilation and window airing.

2.2 Indoor climate

The room temperature is the most important one of the six parameters of the human's general thermal comfort (Fanger, 1970; ASHRAE Standard 55P, 2003; ISO 7730, 2005). To design comfortable houses, the inhabitants should be given an opportunity to control the indoor temperature. In the assessment of indoor climate, in addition to temperature, indoor humidity is an important parameter. Too low indoor relative humidity (*RH*) can cause numerous health problems, like dryness, primarily of the eyes but also of the nasal cavity, mucous membrane and skin. Sterling et al. (1985) suggested that the optimum conditions to minimise the risks to human health would occur in the narrow range of *RH*, between 40% and 60% at normal room temperatures. Other studies suggest somewhat lower *RH* values due to material emissions, odours, perceived air quality and mould growth. Fanger (1971) concluded that the *RH* should not be below 20% because dry air often produces complaints of dry mucous membranes and consequent irritation.

High humidity levels are problematic and can cause serious moisture problems for the building envelope and for indoor climate due to the growth of micro-organisms and house dust mites. Fungal growth experiments on common building and finishing materials indicate that susceptible surfaces can be kept free of fungal growth if the *RH* on the surface is maintained below 80% (Adan, 1994). The critical *RH* level for microbiological growth is 75–95%, depending on the temperature and building material (Johansson et al., 2012, 2013). Su (2006) showed that two possible options are available to control the mould growth in different climatic conditions and housing designs: a conventional method for buildings designed for permanent active thermal controls and a newer method using passive building design and passive controls to keep the indoor *RH* under 80%. The *RH* of the indoor air near surfaces is mainly controlled by the appropriate insulation level and thermal resistance of the house envelope. To design renovation solutions, information about the current situation and hygrothermal loads is necessary. As the indoor *RH* depends on the indoor temperature, outdoor humidity, moisture production and ventilation airflow, presenting humidity loads by moisture or vapour excess as the most independent parameters is proposed in (Kalamees, 2006; Vinha, 2007).

2.3 Airtightness and infiltration

Uncontrolled air movement through a building envelope leads to problems related to the hygrothermal performance, health, energy consumption, performance of the ventilation systems, thermal comfort, noise and fire resistance. Air leakage through a building envelope depends on the air pressure differences across the envelope, the distribution of air leakage places and the airtightness of the building envelope.

Air and moisture convection through the building envelope may impose severe moisture loads on the structure (Kalamees et al., 2009). Indoor air exfiltration in cold climates may cause moisture condensation or accumulation (Kilpelainen et al., 2000; Janssens et al., 2003), leading to microbial growth on materials, change of the properties of the material or even to structural deterioration. Air leakage through a building envelope could introduce outdoor or crawl space airborne pollutants (Airaksinen et al., 2004b) as well as radon gas into the indoor air (Ljungquist, 2005). Uncontrolled air leakage results in an increased air change rate (ACH) and energy use (Jokisalo et al., 2002).

2.4 Interior thermal insulation

Adding an insulation layer to the external wall is a common and effective renovation measure to decrease the heat loss of the house and improve indoor thermal comfort. A need for additional interior insulation exists in old houses that are cultural heritage or located in an area where it is required to preserve the exterior appearance of the house (Arumägi et al., 2011). When an architect or the owner of a new log house wants to expose the natural surface of a log wall on the exterior side, a solution to consider might be interior insulation. This solution may be also used in apartment buildings built of logs if only a few owners want or can carry out deep renovation with additional thermal insulation. In such cases, an insulation layer added on the inside room by room is an easy solution that is the most appealing one visually.

Interior insulation is more complex and not as hygrothermally safe as the widely used exterior insulation (Koski et al., 1997; Pavlík et al., 2009). Increasing the thickness of an insulation layer leads to a decrease in heat loss through the external wall. In general, the risk of failure will be higher if thicker interior insulation layers are used (Vinha et al., 2013). The risk of interior insulation failure means possible mould growth in the wall structure, spread of mould spores, moisture accumulation or water vapour condensation. Spores in indoor air may cause health problems for inhabitants (Platt et al., 1989; World Health Organization, 2009). Theoretically, the moisture flow from the indoor air to the wall can be blocked with a vapour-tight layer on the inner side of the additional insulation, which prevents the development of favourable conditions for mould growth in the wall. In practice the joints of the vapour barrier are not perfect and often owners do not want to use plastic polyethylene sheeting as a vapour barrier. Thus, it is necessary to find a solution where both the risk of failure and heat loss through walls is minimal.

2.5 Energy performance

With the recast of Energy Performance of Buildings Directive (EPBD, 2010) Europe adopted an ambitious vision for the energy performance of its buildings. Lechtenböhmer & Schüring (2010) clearly showed that the improvement of the building shell of residential buildings offers a huge potential for energy savings, which amount to an annual 90 *Mtoe* by 2030 for the EU27. Over two thirds of this enormous potential is located in existing buildings. Therefore, in addition to new buildings, also existing buildings undergoing extensive renovation will have to meet 'very high energy performance' standards by 2021.

Energy renovation of buildings is a multi-criteria approach, where the cost of refurbishment, annual fuel economy after refurbishment, tentative pay-back time, harmfulness to health of the materials used, aesthetics, maintenance properties, functionality, comfort, sound insulation and longevity, etc. should be taken into account (Kaklauskas et al., 2005). The cost-effectiveness, energy performance and environmental impact are typically used in the optimisation of renovation solutions (Diakaki et al., 2008; Anastaselos et al., 2011). In addition to many quantitative values, optimisation may include also qualitative measures. Preserving environmental and historic values of buildings is one of the important considerations in all energy renovation projects.

Many studies (Ascione et al., 2011; Pérez Gálvez et al., 2013) analysed the improvement of energy performance of historic buildings in towns. Much less information is available about energy renovation of traditional rural houses. In their recent research, Bjarløv & Vladykova (2011) demonstrated practical ways of significantly reducing thermal bridges, increasing airtightness, upgrading insulation and adding mechanical ventilation to approximately half of the housing stock without significantly changing the architectural expression or having to relocate the occupants during the renovation for standard family detached and semi-detached wooden houses in arctic Greenland.

Even if there are no official requirements for the energy performance of historic buildings and architectural heritage, owners and inhabitants of wooden rural houses wish solutions to be proposed for improvements of energy performance due to high maintenance costs. Therefore, a multi-criteria approach is a useful tool also in this area. The optimisation of renovation depends on a variety of aspects, such as the initial levels and the final purpose of the energy performance changes, indoor climate, historic and social values, the necessity for renovation from structural, building physical, indoor environment and building service related features. For decision making both are important: improvement as a percentage of the initial conditions and the final level. Whether or not the need for renovation is high, energy related measures are more effective. Therefore, energy performance should be analysed from the state of ‘as built’ up to different renovation measures.

3 METHODS

3.1 Studied buildings

In this thesis, the Estonian rural wooden houses built from 1810 to 1950 are studied (Finnish and Swedish houses presented in articles II and V are left out). Altogether 51 houses (Table 3.1) were examined in different parts of Estonia to have a variety of samples representing different building traditions. Five houses had two floors, others had one floor; 35 barn-dwellings (like in Figure 2.1A and B) and 16 dwellings (like in Figure 2.1C and D) including 5 Setu (an ethnic region in the southeast of Estonia) dwellings were studied. The goal was to have an almost equal number of houses that are in everyday use all year around, summer cottages (unused and unheated during winter) and houses periodically heated and used during the cold winter season. The load-bearing external wall structure of the studied houses is made of horizontal logs. The external walls are covered with wooden cladding in half of the houses and a quarter of the houses have additional thermal insulation layers. Walls are built on a massive foundation wall made mainly of either limestone or granite. All houses have half-hipped or gablet roofs with an angle of around 45°. Most of the floors and ceilings are made of wooden boards on wooden beams. The unrenovated attic floors have 100–200 mm of old traditional insulation on the boarding.

Table 3.1. List of studied houses with main characteristics.

Code	Building year	Net area, m^2	Renovated *	Heating in winter	External cladding / additional insulation
6001	1920	103	Yes	Periodically	No / no
6002	1938	151	Yes	Everyday	Yes / yes
6003	1920	53	No	Periodically	No / no
6004	1932	52	Yes	Periodically	No / no
6005	1920	34	No	Unheated	No / no
6006	1900	34	Yes	Everyday	No / no
6007	1924	127	Yes	Everyday	Yes / yes
6009	1920	94	No	Everyday	Yes / no
6010	1920		No	Unheated	Yes / no
6012	1938	81	Yes	Everyday	No / no
6013	1930	84	No	Everyday	Yes / no
6014		79	Yes	Unheated	Yes / no
6015	1950	107	Yes	Everyday	Yes /yes
6017			Yes	Everyday	Yes / no
6018	1892	50	No	Unheated	Yes / no
6019	1874	48	No	Unheated	No / no
6020	1867	49	No	Everyday	Yes / no
6021	1885		Ongoing	Unheated	No / no

Code	Building year	Net area, m^2	Renovated *	Heating in winter	External cladding / additional insulation
6022	1871	123	No	Unheated	Yes / no
6024	1856	168	Yes	Everyday	Yes / yes
6026	1938	61	Yes	Everyday	Yes / yes
6027	1946	27	Yes	Periodically	Yes / no
6028	1949	73	No	Everyday	Yes** / no
6029	1939	73	No	Periodically	Yes** / yes
6030	1938	56	No	Unheated	Yes / no
6031	1925	93	Ongoing	Unheated	Yes** / no
6032	1930	45	Ongoing	Unheated	Yes / no
6101	1817	57	Ongoing	Everyday	Yes / yes
6102	1850	80	Yes	Everyday	Yes / no
6103	1906	78	Yes	Everyday	No / no
6104		40	No	Unheated	Yes / no
6105	1920	65	No	Unheated	Yes / yes
6106	1901	64	No	Unheated	No / no
6107	1895	104	Yes	Periodically	Yes / no
6108	1919	60	Yes	Periodically	Yes / no
6109	1924	61	Yes	Periodically	Yes / no
6110	1853	67	Yes	Unheated	No / no
6111	1810	83	No	Unheated	No / no
6112	1860	88	No	Everyday	Yes / yes
6113	1908	68	No	Everyday	Yes / yes
6114	1868	180	Yes	Everyday	Yes** / yes
6115		43	No	Periodically	No / no
6116	1920	64	No	Unheated	No / no
6117	1928	78	No	Everyday	Yes / no
6118	1924	103	Yes	Everyday	Yes / yes
6119	1913	149	Partly	Unheated	Yes / no
6120	1829	94	Partly	Everyday	No / no
6121	1891	73	Partly	Periodically	No / no
6122	1899	66	Yes	Everyday	No / no
6123	1902	63	Ongoing	Periodically	Yes / no
6124	1920	94	No	Periodically	Yes / no

* The house was marked as significantly renovated if major renovation works like additional insulation, renovated service systems, replaced floors, etc. were detected.

** Sand-lime brick lining or plastered.

The studied houses had natural, passive stack ventilation. In all of the houses (and most of the rooms) studied, windows could be opened for airing purposes. The majority of the studied houses were heated with wood-burning stoves. The original heating systems had also been wood-burning stoves. Only in a few houses a modern heat pump or boiler heating system was used in addition to original stoves. Most of the buildings were equipped with an electrical boiler to heat domestic hot water (DHW).

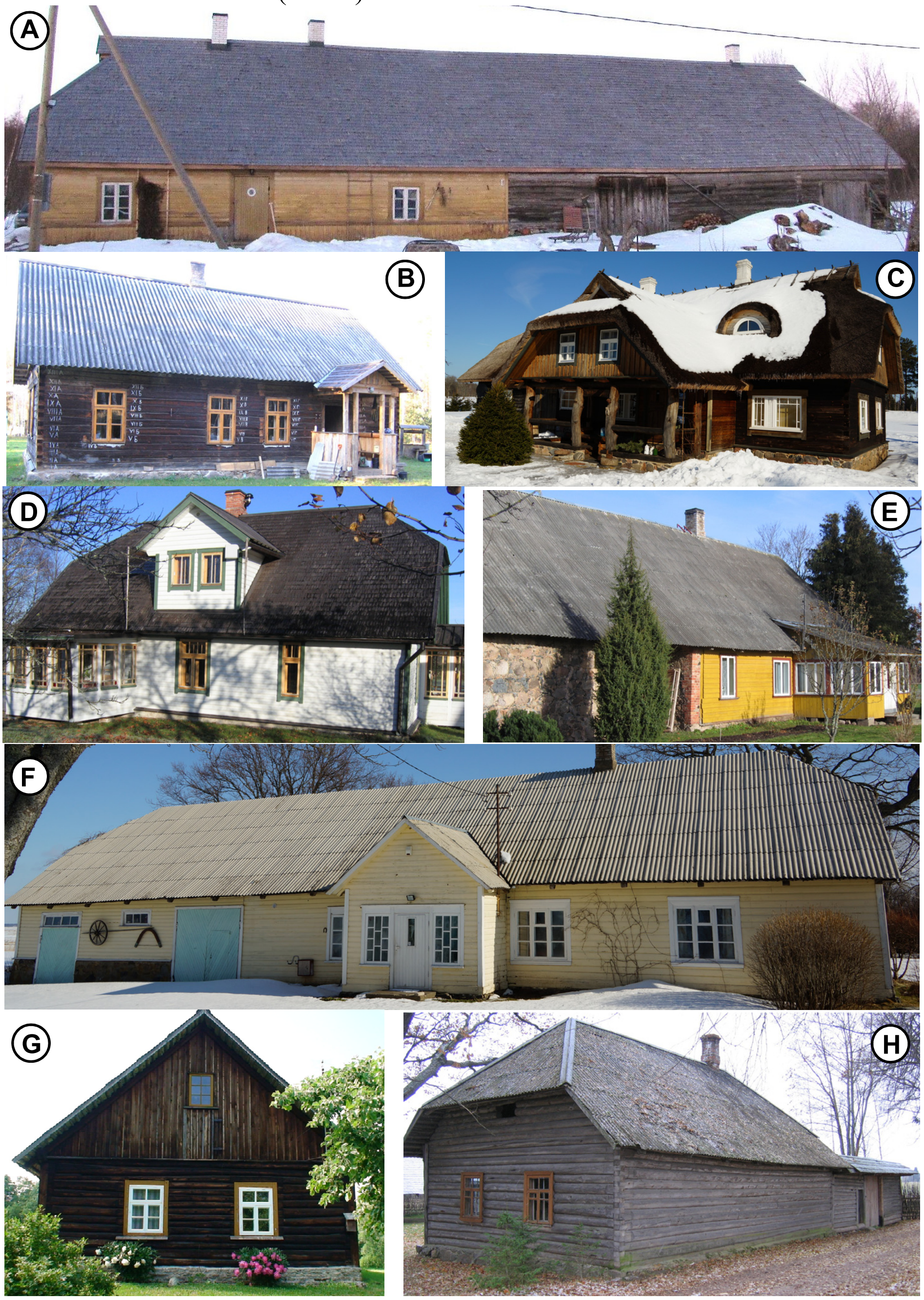


Figure 3.1. Photos of studied buildings: 6107 (A), 6012 (B), 6103 (C), 6007 (D), 6009 (E), 6119 (F), 6110 (G), 6004 (H).

3.2 Indoor hygrothermal conditions

In each house indoor temperature and RH were measured continuously with data loggers at one-hour intervals. Depending on the number of rooms and their usage profile (year-round continuously used houses, periodically used houses and houses unused in winter), from each house 1–4 rooms (typically the main bedroom, living room, kitchen and storage) were selected in the investigation. The outdoor temperature and RH data were gathered from the nearest weather station, including the period from 2008 to 2012. December, January and February were considered as winter months and June, July and August as summer months. Characteristic values of outdoor climate parameters from the time corresponding to the measurement period in houses are presented in a previous study by the author (Alev et al., 2011) and in article III included in the appendix of the thesis.

Indoor thermal conditions in the studied houses were assessed based on the target values from the standards (CR 1752, 1998; EN 15251, 2006). The indoor climate category (ICC) III (acceptable moderate level of expectation, for existing buildings) was selected for comparison. The indoor temperatures during the heating period have to be in the range of 22 ± 3°C. During the summer the indoor temperature dependence on the outdoor temperature according to the standard (EN 15251, 2006) was used as old houses have no mechanical cooling systems. The indoor RH values in the range of $20\% < RH < 45\%$ during winter and in the range of $30\% < RH < 70\%$ during summer were selected as target levels based on the literature review. The percentage of time when the criterion was exceeded was used for thermal evaluation purposes. Exceeding the target values up to 5% of the time was allowed according to EN 15251 (2006).

The values of the internal moisture excess (difference between the indoor and the outdoor air water vapour content) Δv, g/m^3, were calculated on the basis of the measured results of the indoor and the outdoor temperatures and RH:

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

where ν_i – the indoor air water vapour content, g/m^3
ν_e – the outdoor air water vapour content, g/m^3
G – moisture production indoors, g/h
q_v – ventilation airflow, m^3/h

In addition to the measurements, a questionnaire was completed about each occupant's habits and the usage of the house (installed appliances and equipment, normal presence of occupants, moisture sources, use of shower, sauna or bath etc.), typical complaints and symptoms related to indoor air quality (too warm, too cold, unstable temperature, cold floors, too humid, too dry, draught, stuffy air, bad smell, inadequate ventilation, dust and dirty surfaces, noisy ventilation system, poor lighting, unequal temperature in the rooms, static electricity, vertical temperature gradient, noise of the heating system etc.) and occupants' opinion about renovation solutions to obtain an overview for measurements and information about user satisfaction. Statistically significant relations were analysed based on Student's t-test, where $p < 0.05$.

3.3 Airtightness and infiltration

The airtightness of the building envelopes was measured with the fan pressurisation method (EN 13829, 2000). In addition to a short air leakage test, the passive tracer gas method (described in standards Nordtest, 1997; ISO 16000-8, 2007) was used in selected houses to study the air leakage under everyday usage. The primary measured value is called 'local mean age of air'; it is equal to the inverted value of the local ACH of the building (used in this thesis). The ACH during normal house usage was measured with the passive tracer gas method in 10 houses during 32−35 days in the summer period and in 11 houses during 21−26 days in the winter period. Places of air leakage and thermal bridges and their distribution were determined with thermography measurements (EN 13187, 2001) during winter.

Relative reduction of the surface temperature was used to determine air leakage locations. Relative reduction of the surface temperature (Δt_s, %) shows the ratio of the difference between the indoor (t_i, °C) and outdoor (t_e, °C) air temperatures to the difference between internal surface temperatures of the building envelope measured before (t_{si1}, °C) and after (t_{si2}, °C) the depressurisation (Kalamees et al., 2008):

$$\Delta t_s = \frac{t_{si1} - t_{si2}}{t_i - t_e} \times 100\% \tag{2}$$

More details about airtightness measurements can be found in article VI.

The measured infiltration rate was compared to the calculated infiltration rate roughly approximated by the standard correlation dividing the building leakage rate n_{50} by a case-dependent denominator x:

$$n_{\mathrm{inf}} = \frac{n_{50}}{x} \tag{3}$$

The factor x is the product of several correction factors (using the principle shown in (Sherman, 1987)): climate zone, wind condition, leakage distribution, number of storeys, flow exponent and ventilation balance (Jokisalo, 2008).

3.4 Interior insulation

There are many parameters that affect the hygrothermal performance of interior insulation: thickness of the insulation layer, thickness of the log wall, air leakage rate of the log wall, indoor and outdoor climate parameters such as temperature, *RH* and the moisture excess, water vapour transmittance of the wall layers and the initial moisture content (*MC*) of the logs. To analyse the hygrothermal behaviour of the interior insulation on log walls two independent field measurements were made. The first one (Alev et al., 2012), a parametric study (referred to as 'PS case' below), was made on an old log wall with mineral wool with the aim to analyse all affecting parameters in detail with one common insulation material − mineral wool. The second measurement (Alev et al., 2014), a material study (referred to as 'MS case' below), was made on a new log wall with the aim to compare three insulation materials: mineral wool, cellulose fibre and reed mat. The reed mat insulation was the only version where no special air and vapour barrier was used and it was covered with clay plaster instead of gypsum board used in the other versions. During the PS case the indoor moisture excess was low and during the MS case high. Calculation models of both measurement cases were made with the simulation software WUFI using measured indoor and outdoor climate data. The detailed measurement setup, model parameters and model validation results of the PS case are presented in article III and of the MS case in (Alev et al., 2014).

The main characteristics of the calculation model made for the PS case are shown in Figure 3.2 and the detailed material properties in article III. The material properties for the MS case are shown in article IV. Characteristic properties of materials used in simulation are shown in Table 3.2, except the various water vapour barrier materials described below (vapour diffusion thickness S_d values are given in Table 3.3 and Table 3.4). The critical surface (Figure 3.2) in the wall in terms of moisture safety was the interior surface of the log wall in direct contact with the insulation layer. The affecting finishing layer was gypsum board. The air and vapour barrier provided airtightness for the wall.

Table 3.2. Main hygrothermal properties of materials used in simulation

	Wooden log	Mineral wool	Cellulose fibre	Reed mat	Clay mortar	Gypsum board
Bulk density ρ, kg/m^3	390	60	60	136	1568	850
Porosity f, m^3/m^3	0.75	0.95	0.95	0.9	0.41	0.65
Specific heat capacity c, J/(kg·K)	1600	850	2000	2000	488	850
Thermal conductivity λ, W/(m·K)	0.09	0.04	0.037	0.075	0.48	0.2
Vapour diffusion resistance factor μ, -	108	1.3	1.5	2.0	20	8.3
Built-in moisture w, kg/m^3	45	0.02	8.0	6.0	100	2

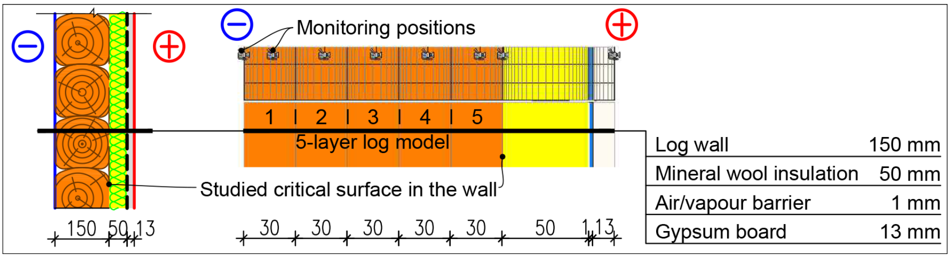


Figure 3.2. Section of an interiorly insulated log wall and a screen capture of the calculation model in WUFI (model for the PS case).

The wall was considered airtight in the calculation model. An Estonian moisture test reference year (Kalamees et al., 2004), critical in terms of mould growth in Estonia, was used for the outdoor climate after a validation of the model with the measured outdoor climate.

The calculation results show a substantial dependence of airtightness on the quality of the selected input data. It is hard to define the ‘average log wall’ because a variety of building techniques have been used depending on the time of construction and the building traditions in different regions. In addition to building methods, also the building quality is variable. It is important to take into account the variability of different parameters in real structures to ensure that the selected solution is hygrothermally safe and reliable.

To identify hygrothermally functioning boundary conditions, multiple parameters were varied, as shown in Table 3.3 and Table 3.4 (PS and MS case models, respectively). The indoor temperature reference level is based on measurement results from previous studies (Alev et al., 2011; II), where the average indoor temperature during the cold period (outdoor temperature $t_e < 15$ °C) was 19 °C (Figure 3.3A). The average indoor temperature line of heated houses is based on results shown in Figure 4.9. Based on the national appendices to the standards EN ISO 13788 (2012) and EN 15026 (2007), the indoor humidity load level chosen represents the average measured level $\Delta v_i = 5/1.5$ g/m^3 at outdoor temperatures below +5 °C/above +20 °C (Figure 3.3B). Average measured moisture excess and 90% level of measured moisture excess in Figure 3.3B are based on measured values described in chapter 4.2.3. Equivalent vapour diffusion thickness (S_d) values represent the following materials: 0.01 m – no special vapour barrier; 0.1 m – similar to bitumen-impregnated paper; 1 m and 2 m – levels similar to smart vapour retarder membranes; 10 m – laminated paper; and 100 m – similar to plastic polyethylene sheeting.

Table 3.3. Varied parameters in the PS case simulation model. The grey background indicates the RC.

Parameter	Reference	Versions (values)					
Indoor humidity load Δv, g/m^3; $t_e < +5$ °C / $t_e > +20$ °C	5/1.5	1/-0.5	2/0	3/0.5	4/1	5/1.5	6/2
Average indoor temperature during winter t_i, °C	19	18	19	20	21	22	23
Thickness of log wall d_log, mm	150	100	125	150	175	200	225
Thickness of additional insulation d_ins, mm	50	25	50	75	100	125	150
Initial *MC* of logs w, %	14	14	15	16	17	18	19
Vapour diffusion thickness S_d, m	2	0.01	0.1	1	2	10	100

Table 3.4. Varied parameters in the MS case simulation model. The grey background indicates the RC.

Parameter	Reference	Versions (values)								
Indoor humidity load Δv, g/m^3; $t_\mathrm{e} < +5$ °C / $t_\mathrm{e} > +20$ °C	4/1		4/1			5/1.5			6/2	
Average indoor temperature during winter t_i, °C	19									
Thickness of log wall d_log, mm	150	100		125		150		175		200
Thickness of additional insulation d_ins, mm	50	50		75		100		125		150
Initial *MC* of logs w, %	17	15	16	17	18	19	20	22	24	26
Vapour diffusion thickness S_d, m	2		0.01		1		0.25−25		18	

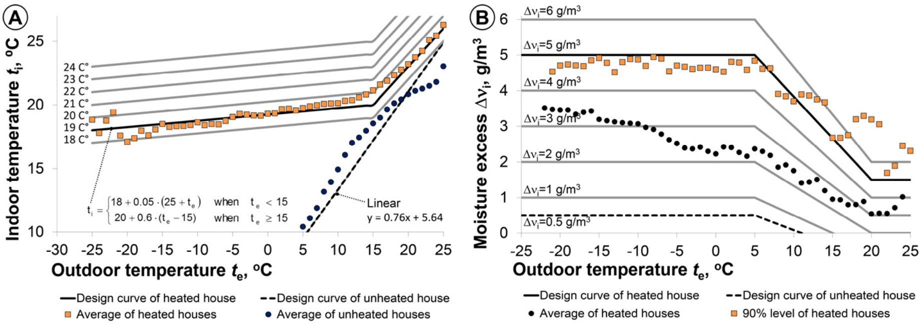


Figure 3.3. Dependence of the indoor temperature on the outdoor temperature in wooden houses (A) and 90% level of weekly maximum moisture excess at the corresponding outdoor temperature (B). Figures are developed based on measurements presented in II.

Moisture safety assessment was based on the risk of mould growth between logs and the interior insulation. The temperature and *RH* hourly output from the simulations was post-processed, and the mould growth index (*M*) was calculated for the critical surface in the wall based on the improved *M* calculation model (Hukka et al., 1999; Viitanen et al., 2007, 2011). The index *M* represents the possible level of mould growth on a wooden surface according to the numeric scale. The *M* in the critical point in the wall is presented in Figure 4.14, Figure 4.25, Figure 4.26 and Figure 4.29−Figure 4.34. The *M* values below 1 are safe. More details of *M* calculation are presented in article III.

Firstly, before starting interior insulation work in the desired month, we checked whether it was hygrothermally safe (calculations with the PS case). The objective was to identify the month during which built-in moisture levels in a log wall are minimal. Over the course of a year, both indoor and outdoor *RH* change and have a different effect on the *MC* in a log wall. Twelve year-long simulations were made, with the start time matched to the beginning of each month. The structure consisted of a 150 mm thick log wall only, divided into five equal 30 mm thick layers (Figure 3.2, without any insulation). The outside was exposed to the outdoor climate, whereas the inside was exposed to either a free-floating climate (representing an unused house or a summer cottage before renovation) or a warm climate (representing continuously heated houses). Design curves for both cases are shown in Figure 3.3.

Secondly, the drying-out time of built-in moisture was analysed (calculations with the PS case). The calculation period started at the beginning of June. Both unheated (summer cottage) and heated (regular house) cases were analysed. The indoor temperature of unheated houses was chosen based on the measurement results from Alev et al. (2011). The design curve with the formula for unheated houses is shown in Figure 3.3A. In winter, based on the same study, $\Delta \nu_i$ in the unheated houses was chosen to be 0.5 g/m^3. For the case of regular houses the average indoor temperature in heated houses and $\Delta \nu_i = 5/1.5$ g/m^3 were used. The log wall was considered with a constant *MC* at the beginning of the calculation period. The *MC* in logs was varied from 14% to 19% with a 1% increment.

A parametric study (PS case) was conducted to analyse the risk of mould growth on the critical surface: the inner surface of a log. One parameter was varied at a time, with the other parameters being based on RC. The output was given as *M* change over five years (line). When two or three parameters were varied, the output was given in a tabular form, showing the maximum *M* value for each combination over five years. A period of five years calculated with the moisture test reference year was considered long enough to achieve stable yearly hygrothermal variation with most of the calculated combinations. A material comparison study (MS case) was conducted to compare three different insulation solutions: mineral wool, cellulose fibre and reed mat with clay plaster. Five parameters were varied as shown in Table 3.4, the calculation period was one year starting from June.

3.5 Energy performance

The energy performance of buildings in Estonia (Vabariigi Valitsus, 2012) is expressed as annual primary energy consumption (*PE*) (kWh/(m^2·a)). The *PE* is calculated from the total delivered energy consumption (*DE*) by using energy carrier factors for fossil fuels (1.0), wood and biofuels (0.75) and electricity (2.0). Additionally, the *PE* includes energy for lighting and household electricity. The reduction of the annual *DE* and the energy performance value from original levels was used:

- 20% reduction from the original *PE*;
- 60% reduction from the original *PE* (leads to the requirement of major renovation for the Estonian sample house (Vabariigi Valitsus, 2012);
- 80% / 88% reduction from the original *DE*.

The renovation alternatives of energy performance were modelled using the IDA indoor Climate and Energy 4.2 (IDA-ICE) building simulation software. The standard usage profile according to Estonian energy calculation regulations was used in building simulation (details in article V).

For selecting energy renovation measures, simulations were made in different phases under standard uses of the house:

- Basic situation: non-renovated (‘as built’) conditions;
- Influence of a single energy renovation measure to find out its relative importance:
  - measure focused on an effective thermal envelope,
  - measure focused on effective building service systems (HVAC),
  - measure focused on the energy source and the use of renewable energies;
- Energy renovation packages were calculated for different scenarios for different energy saving levels.
  - Package I: to save cultural heritage, the least changes to the external appearance of the house were the purpose: insulation is added starting from the less visible parts of the external surface, such as the roof, floor, windows etc. (concentrating on the preservation of the external milieu value upon the insulation of the building envelope). The replacement of old structures is allowed. In that case, it is necessary to copy the dimensions and proportions of the original building features;
  - Package II: concentrating on the improvement of thermal comfort (decreasing thermal transmittance of structures $U < 0.7$ W/(m^2·K) to avoid asymmetric radiation and draft). Energy renovation starts with the insulation of the building envelope and later moves into service systems;
  - Package III: improvement of energy performance starts from building service systems and later moves into the structures.

The ventilation airflow in simulation was 0.35 $l/(s{\cdot}m^2)$ for the non-renovated case and in single renovation measures without improvement of ventilation, representing ICC III (an acceptable, moderate level of expectation for indoor climate (EN 15251, 2006)). Because the ventilation performance was insufficient in most energy renovation packages of rural houses, the renovated ventilation was represented by ICC II (normal level of expectation for indoor climate: 0.42 $l/(s{\cdot}m^2)$).

If the renovation measure enabled a reduction in air leakage, the air leakage rate of the building envelope was assumed to decrease from the original value by up to 60% (Chan et al., 2012): 5% at the insulation of stone walls; 10% at the renovation of windows and additional thermal insulation for slab on the ground; 15% in case of new windows, insulation of attic floor and base floor with ventilated crawl space; 20% at the insulation of log walls. The air leakage reduction components were estimated by the author based on statistical analysis of the distribution of measured air leakage places. The thermal transmittance of every envelope part was calculated based on the technical survey of houses.

At room heating with stoves or an air–air heat pump (AAHP), an electrical boiler was used for DHW. In all the other cases the same energy source was used for room heating and DHW. As floor heating requires the rebuilding of all floors, energy renovation measures with a boiler and a heat pump were calculated with radiator heating.

4 RESULTS

4.1 Condition of houses

The following technical description is based on the survey in 51 houses in Estonia mainly built before World War II. The average construction year for these houses is 1903 (1810−1950), and the average net area of the living space in them is 80 m^2 (34−180 m^2). Half of the houses examined are in everyday use all year round, a quarter are summer cottages (unused and unheated during winter) and a quarter are used periodically also during the cold season. The two main timber species used for building log walls and other wooden construction parts are Norway spruce (*Picea abies*) and *Scots pine* (*Pinus sylvestris*). A more detailed description of survey methods is given in article I.

4.1.1 Foundation and base floor

Nearly half the houses had original foundations built of limestone, with the rest built of granite masonry. A few houses had reconstructed foundations where concrete had been used. A couple of dry-laid stone foundations (no mortar between stones) were identified. Usually, the foundation depth into the ground was no more than 50 cm; often it was less. The foundation width ranged from 30 to 60 cm. The height of the section of the foundation above the ground (foundation wall) ranged from 0 to 60 cm. In half the houses, the foundation wall height was below 20 cm. The houses examined have projecting or receding basement walls. A quarter of the houses had an additional mortar layer above the foundation. Typical foundation and base floor solutions are shown in Figure 4.1.

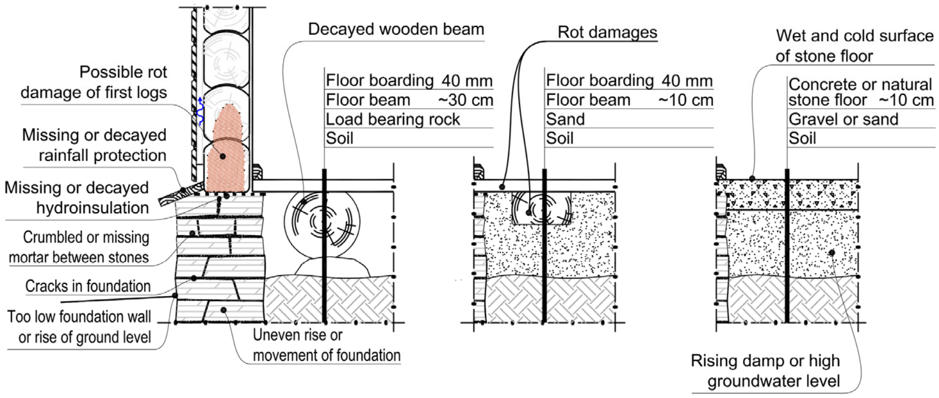


Figure 4.1. Section of a foundation, base floor and external wall. Main construction elements and common damage.

Low foundation depth in the ground can cause undesirable rising and movement of structures due to the freezing of the ground. If the foundation depth in the ground is less than that of the frozen ground in winter, yearly frost boils may damage the foundation (Figure 4.2). Also, natural stones may decay due to physical or chemical weathering. There may be cracking due to the different expansion of stones when granite and limestone are used in conjunction.

Foundations covered with a wide wooden board and with lime-mortar-filled joints between stones were in the best condition. The wooden board protects the foundation wall from rainwater. There were fewer problems with the foundation on the same plane with the wall or even inside the wall plane.

Figure 4.2. Uneven settlement of the foundation and an excessively low foundation wall (A) and large cracks in the foundation due to the soil freezing and damaged water boarding (B).

Selected base floor designs and common damage are shown in Figure 4.1. Most floors with crawl space are supported by roundwood beams and wooden boards. Floor beams can be laid on big stones (Figure 4.3A) or directly on sand (Figure 4.3B). The study identified both old uninsulated concrete floors cast directly on sand and floors made of natural limestone slabs in a few houses (Figure 4.1). Old unrenovated concrete and natural stone floors are cold and damp. Wet rooms usually have concrete floors covered with ceramic tiles without a waterproofing layer and drainage layer from gravel or crushed stone. Therefore the floor is continuously wet both due to capillary rise and shower water leaking into the concrete layer.

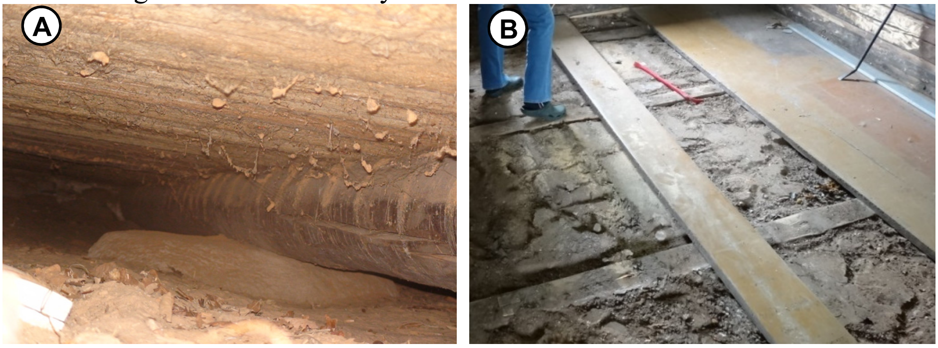


Figure 4.3. Wooden floor on roundwood beams (A). Floor beams inside damp soil (sand) (B).

In many examined houses, wooden beams had rot damage (paper I: Figure 4 right). Therefore, the effective cross-section area of the beams had decreased and the floors had sagged. Hygrothermal conditions in the crawl space were almost always favourable for mould growth or even rot. These favourable conditions may be due to one or more causes:

- very low air change in the crawl space indicating absent, closed or too few ventilation openings through the foundation wall;
- temporary free water in the crawl space indicating an excessively high level of groundwater or freshet (rain or melted snow) entering the crawl space;
- wooden beams in contact with wet soil indicating that the inclination around the house does not guarantee that water flows away from the house or that there is no soil layer (20 to 25 cm of gravel or crushed stone) to effectively reduce capillary rise; capillary rise may cause problems on concrete slabs on ground;
- insufficient drainage system.

Additional insulation of the floor definitely decreases heat loss and raises the surface temperature of the floor. The temperature in the airspace between the insulated floor and soil will decrease causing an increase of *RH*. Whilst lower temperature in the airspace decreases the moisture evaporation rate from soil to the airspace, the insulation layer decreases the height of the airspace lowering the ACH in the airspace that could lower the *RH*. Often drying out moisture and reducing the radon concentration in the crawl space are not addressed. The study by Alev et al. (2015b) showed that joints between the floors and the external walls are very leaky; thus, almost no attention has been paid to the airtightness of the floor constructions.

4.1.2 External walls

Two typical external wall solutions with main damage are shown in Figure 4.4. Walls of old rural houses are typically built from horizontal round or hewn logs. The diameter of roundwood logs ranges from 15 to 25 cm. Horizontal joints between logs were originally sealed with tow or moss.

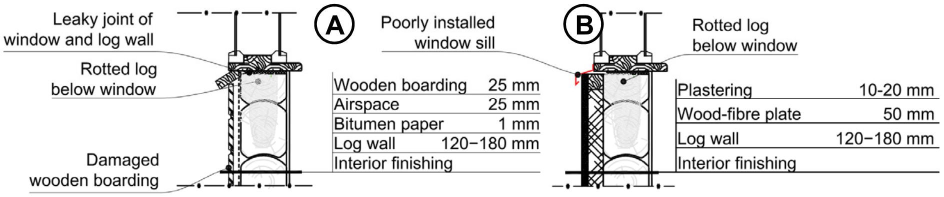


Figure 4.4. Typical external wall with wooden boarding (A) and plastering (B).

In about a quarter of the houses studied, the log walls have no covering layers; half have cladding on the external side of external walls. About a quarter of the houses are renovated and include a wind barrier and insulation layers in addition to the external cladding. A couple of the houses have plastered external walls or additional silicate masonry for rain protection. To protect the log walls from the rain, in a few houses horizontal or vertical wooden boarding fixed on battens or directly on the log is used. Vertical battens between the boarding and the log walls or the wind barrier (in case of an externally insulated wall) are considered the best solution because the natural air movement in the air gap between the boarding and the wall helps to dry out the wall.

A special wind barrier is not used in the external walls. Based on airtightness measurements (VI), internal plaster or tightly installed plywood boards decrease the air leak. In more than a half of the houses, the log wall is unfinished from inside. In a few houses, the lower part of the wall is covered with vertical boarding (to a height of ~70 cm), which often hides the masonry wall (replacing damaged lower logs) made of expanded clay, lightweight concrete blocks or silicate stones. Wooden elements are sensitive to high *MC*. Because of low foundation walls, damaged waterproofing and water coming from the ground, the lowest rows of log walls often suffer wood decay and wood-rotting fungi or insects. Therefore the lowest rows of logs have in many cases been replaced with new logs or stone walls. Frequently there is damage around the windows (to a lesser or greater extent, half the houses have this problem). Most often, the log directly below the window is rotten, damaged by a missing or decayed subsill as water falls from the window directly on this log.

Most problems are caused by excessively high moisture loads or poor construction quality. Critical areas and causes of damage in external walls include

- excessively low foundation walls causing severe rainwater and snow loads on the external surface and damage to the first log rows;
- uneven settlement of the foundation causing cracks in the wall;
- missing waterproofing layer between the foundation and the first log row causing high moisture levels in the first log rows and rot damage;
- excessively short eaves causing rainwater to reach the facade;
- no or damaged rainwater piping causing local water damage to the wall or facade;
- defective or incomplete window sills or other rainwater management systems causing rot below the window or near other wall parts affected by flowing water.

The surrounding ground level has often risen due to the increased humus layer near the house, ground planning works, road construction etc., due to which the foundation wall ends below the ground level and the log wall is in contact with the soil in a few cases. Rising ground levels are often a result of poor cleaning of the area surrounding the house. Log rows in contact with soil decay quickly and induce additional settlement in the wall, widening wall cracks and bringing about unexpected settlement of windows and doors.

In many cases the waterproofing layer between the foundation and the wall (Figure 4.1) is damaged or was not laid at all during the original construction. In older houses the waterproofing was probably made of birchbark, but this is fully decayed now and moisture rises directly from the foundation to the first logs. Mainly for this reason, in half the houses moisture damage is evident in the first log rows. In many houses a mortar surface tilting outwards has been built on top of the foundation edge to direct rainwater away from the wall (Figure 4.5B). If any water penetrates between the log wall and the additional concrete edge, the drying of the log surface will take much longer and the moisture will increase the risk of damage to the first log rows. The bitumen paper behind the external boarding that should stop the rain load on the log may be broken and so prevents the air movement behind the boarding (Figure 4.5A).

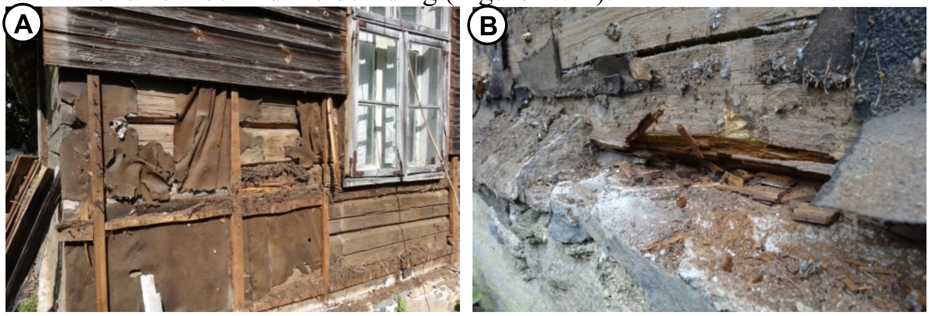


Figure 4.5. The bitumen paper behind the external boarding (A). Missing waterproofing between the foundation and the log and the mortar above the log result in rot damage to the lower log (B).

4.1.3 Ceiling, attic and roof

Typical ceiling solutions of the attic floor in studied houses are shown in Figure 4.6. The load-bearing structure of the ceiling of the top floor is made of hewn wooden beams. The large attic space between the roof and the ceiling is often used for storing things that are not needed. The boarding (often upper rough boarding) is fixed on the wider edges (or added slats) of the bottom of the beams. Sometimes, a second finishing layer is added below the rough upper boarding made of painted matchboards, painted plaster or a painted plywood layer. The average thickness of the insulation layer (sand, sawdust, flax shives or hay dust mixed with clay or lime) on the upper boarding is 20 cm. When the houses were built, the attic was often used to store hay for animals. Hay also acted as insulation in winter; however, when animals were not raised on the farm anymore, old hay was removed from the attic (for an example, see Figure 4.7A). Hence, the thermal resistance of the ceiling is lower than it used to be.

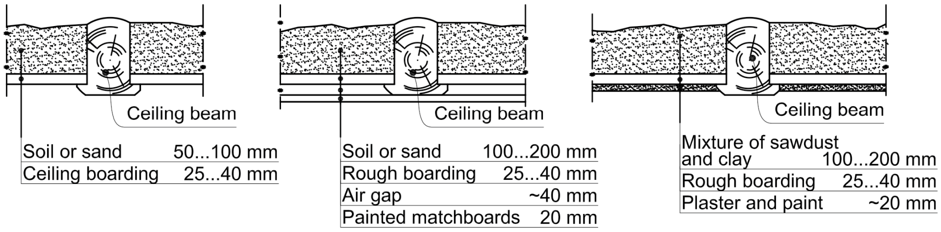


Figure 4.6. Typical attic floors.

In most renovated houses, old ceiling boarding has been cleared of old paint or replaced with new boarding. Additional thermal insulation of mineral wool or expanded clay aggregate has been added to the original insulation layer, or the original layer has been replaced. Only in a couple of renovated houses, a correctly installed wind barrier above and air/vapour barriers below the insulation were used. If the attic level was renovated as a living space, the ceiling/roof was insulated with a 100 to 150 mm mineral wool layer between the rafters and finished with painted/papered gypsum board or a thin matchboard layer.

A leaky ceiling increases heat use. In buildings where the old solid ceiling insulation mixture had been replaced with only mineral wool, sawdust, hay or other unknown dust, the airtightness was low. When the original insulation solutions were compared, the best airtightness was achieved with a mixture of clay and flax shives. Renovated rustic-style ceilings made of two-layer overlapping unedged wooden boards had the lowest airtightness. Ceilings covered with continuous plaster layers or plywood had better airtightness. Often during renovation old plaster or plywood layers were removed and the boarding behind it was cleaned and varnished, whereupon the airtightness of the house declined considerably. In a couple of buildings, the joint between the ceiling and the chimney is leaky, causing heat loss through cracks and also fire safety issues.

If the ceiling is insulated with soil or sand and if there are water leaks through the roof, insulation may be wet permanently (or for extended periods). Wet insulation causes wooden ceiling details to rot (Figure 4.7B). Insulation particles (sawdust, sand or mixtures thereof) fall into rooms through cracks in the ceiling boarding, and cleaning this dust causes extra work and inconvenience for inhabitants. In some cases the falling dust problem is solved with a double ceiling below the original one, made of matchboards or plywood. In a few renovated buildings, the old insulation has been replaced and/or an air/vapour barrier has been added below the insulation layer.

Figure 4.7. Fire risk in the attic (A). Rot damage to wooden ceiling details insulated with soil (B).

Rural houses have traditional half-hipped or gablet roofs. The roof angle is usually 45˚ ± 10˚. Roofs were originally covered with thatch or wooden shag shingles (Figure 4.8A). Later, most wooden shag shingle roofs were covered with asbestos cement boards (with the old roof covering usually left underneath) (Figure 4.8A). Laying asbestos cement boards over old roofs is faster and cheaper than replacing old roofs using the original solution. Thatch roofs are mainly replaced if needed, and in only one case it had been also covered with asbestos cement boards. The thickness of the thatch layer is usually 30 cm. In a few renovated houses, the roof has been covered with steel plates or asphalt shingles.

In renovated houses, the attic space is put to use as a living space, and thus the roof has insulation between the rafters. Old hewn rafters are replaced with new sawn rafters measuring 50 × 150 to 200 mm.

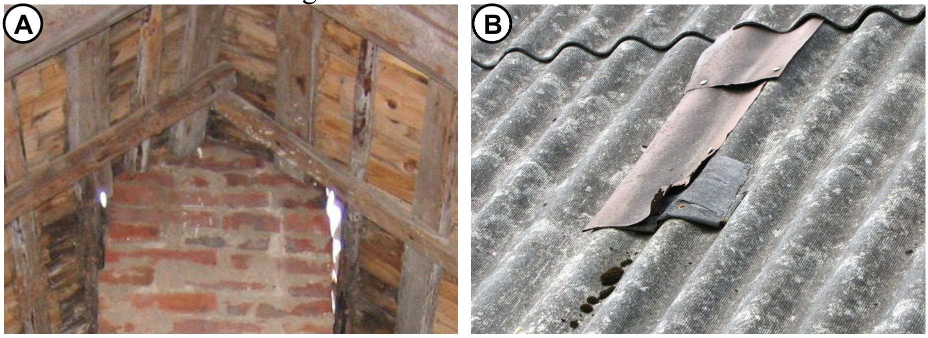


Figure 4.8. Original roof cover of wooden shag shingles (A − from underside) was frequently covered with asbestos cement boards (B). Typical leaks: around the chimney (A) and due to excessively old roof covering (B).

The main function of the roof is to protect the house from precipitation. Water leaks in roof covering are the main cause for roof construction damage. The main causes for water leaks include:

- old roof covering;
- poor roof maintenance (moss and leaves on the roof);

- faulty fastening of the roof covering;
- temporary repairs of leak areas (Figure 4.8B);
- extensive settlement of the load-bearing construction;
- defective edges or covering components;
- holes or cracks near components passing through the roof (chimneys, ventilation pipes, antennas etc.).

Small leak areas may cause significant wet damage. Although the amount of water leaking through a small leak area is small during each instance of rainfall, it provides favourable conditions for the growth of rot or mould. It is possible that not all small leaks are visible from the inside. An actual water leak through the roof was found in only one house not used for years where renovation had just started. In all the other houses, the roofs had been either periodically repaired or replaced when needed. A temporary but nevertheless necessary solution for repairing the roof is shown in Figure 4.8B.

About a fifth of the houses had problems related to the joint between the chimney and the roof. In most houses, the penetration through the roof was on the ridge, which simplified waterproofing solutions, as there was no need to shunt water around the chimney. In two houses, the chimney had been erected at an angle to have chimney penetration through the roof on the ridge when the base of the chimney is not on the centre line of the building. Nevertheless, there were moisture damaged wooden roof components near the chimney because a few chimneys did not have the correct flashings above the roofline.

4.2 Indoor climate

4.2.1 Temperature conditions

To review the thermal conditions in continuously used old rural houses, the dependence of the indoor temperature (t_i) on the outdoor temperature (t_e) was analysed. Results are illustrated in Figure 4.9.

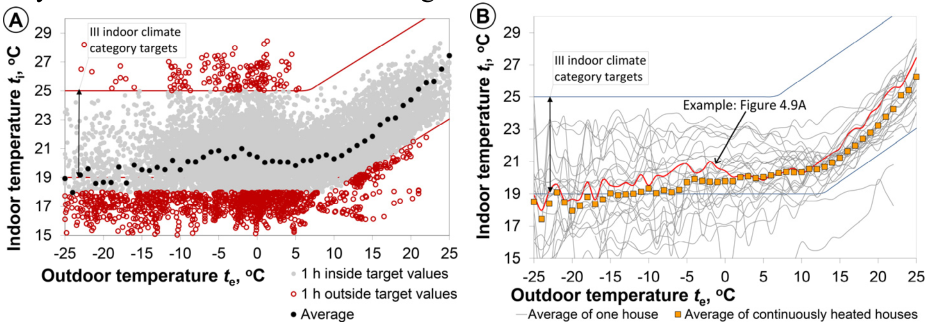


Figure 4.9. Dependence of the t_i on the t_e in one measured house (A) and in all continuously used houses, including average value (B).

The average indoor temperature in the winter period (December, January, February) was 19.4 °C. In the summer period (June. July, August), the average temperature and most of the temperature curves of the houses were in the range of the target values of the standard EN 15251 (2006). The average indoor temperature in the summer period was 21.1 °C. The average indoor temperatures in periodically heated and in unheated houses are lower than in continuously used houses even in the summer period. The average indoor temperature was below targets when the outdoor temperature fell below −20 ºC. The variation of indoor temperature was mainly caused by high heat loss (air leakage rate and thermal transmittance) of the building envelope and periodic heating. Inhabitants perceive the variation as periodic (daily) low and high indoor temperatures. The average daily variation of the indoor temperature (difference between minimum and maximum indoor temperature during 24 h) during the summer period was 2.0 °C both in the houses used continuously all year round and in the unheated houses. In the winter period the average daily variation of the indoor temperature in continuously used houses was 4.2 °C. Compared with the summer period during the winter period the variation was 2.2 °C higher in continuously used houses ($p = 3\times10^{-7}$) and 1.0 °C lower ($p = 1\times10^{-5}$) in unheated houses.

Indoor temperature in continuously used houses was compared with the target values (EN 15251, 2006) of the ICC III during summer (Figure 4.10A) and winter (Figure 4.10B). The room temperature in rural houses was quite often too low all year round: 33% of the time during winter and 17% of the time during summer. Nevertheless, it was too high in a few houses: 8% of the time during winter and 1% of the time during summer. If it is acceptable to exceed the indoor climate target values by up to 5% of the time (EN 15251, 2006), then the indoor temperature will not meet the ICC III values in 70% of all continuously heated houses during summer and in 93% during winter (Figure 4.10). The main reasons for lower indoor temperatures are large heat losses of the building envelope, stoves not properly heated due to fire safety aspects, savings on energy bills and wearing warmer clothes. The stoves are designed to daily average outdoor temperatures in the cold period and not extreme temperatures; therefore there is not sufficient heating power for lowest outdoor temperatures (Figure 4.9B).

The most important indoor climate related problems reported by inhabitants were unstable or too low air and surface temperatures, see Figure 4.11 (all Estonian houses presented in article II).

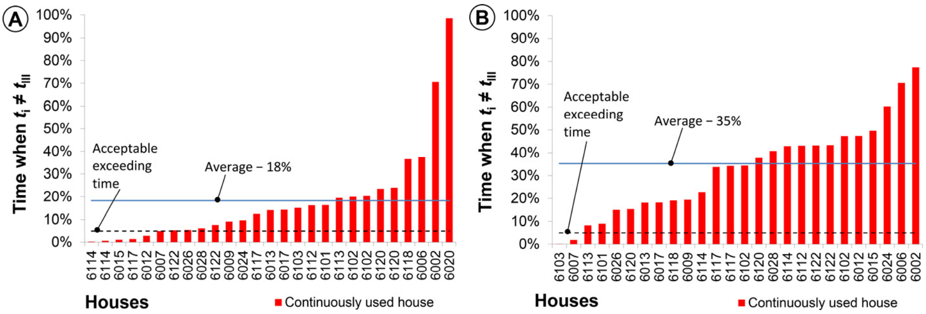


Figure 4.10. Percentage of time when t_i exceeds target values for indoor climate of ICC III (t_{III}) in the summer period (A) and in the winter period (B) in all continuously used houses.

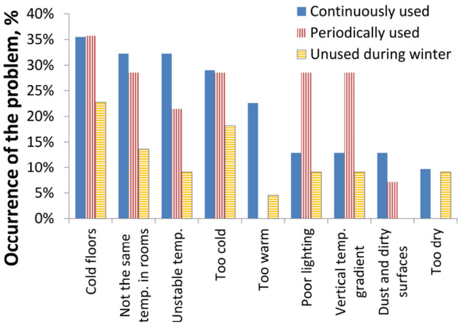


Figure 4.11. Occurrence of indoor climate problems in all houses.

Statistically significant relations were found between the measured indoor climate-related parameters and user complaints about the indoor climate by Student's t-test analysis (for continuously used Estonian houses presented in article II). Significantly ($p = 0.02$) higher reporting by inhabitants concerned the condensation on windows in houses that had lower correspondence of indoor temperatures to target values (III ICC in EN 15251 (2006) and CR 1752 (1998)). Condensation on windows depends on several factors: thermal transmittance of windows, interior surface resistance, indoor humidity loads, indoor and outdoor temperature conditions. Decreasing indoor temperature decreases also the temperature of the window surface, which may fall below the dew point temperature. Leaky windows aggravate the situation. Moreover, leaky windows influence also temperature correspondence to target values.

In half of the houses inhabitants had complaints about an unstable indoor temperature. This complaint was registered in most of the houses with stove heating. The heat loss due to the higher air leakage rate of the house resulted in low indoor temperatures in the morning. To avoid low temperatures in the morning, inhabitants heated more, which resulted in periodic overheating. It was found that when the inhabitants reported too high indoor temperatures, the air leakage rate q_{50} was 87% higher ($p = 0.04$) and when the inhabitants felt that the indoor temperature was unstable, the air leakage rate was 74% higher compared to the houses with no such complaints.

4.2.2 Indoor humidity: stability and risk of mould growth

The dependence of the indoor *RH* on the outdoor temperature (Figure 4.12) was analysed in the same way as the dependence of the indoor temperature on the outdoor temperature. Most of the average values of *RH* in continuously used houses were in the range of the target values (20–45% during winter and 30–70% during summer). Only during extremely cold periods, it may be too dry and in spring or in autumn too humid in some houses. The higher humidity during autumn and spring may be a concern only in houses with thermal bridges with very low inner surface temperatures as it causes mould growth risk. The average *RH* in the winter period was 35% and in the summer period 61%.

The *RH* was high in almost all unheated houses (Figure 4.13) and in many periodically heated houses. The critical *RH* for mould growth depends also on the temperature (Hukka et al., 1999). Periods with high *RH* and very low temperature are not critical for mould growth. The mould growth risk existed in 6% (three houses) of all the houses and in 15% of the unheated houses (Figure 4.14A).

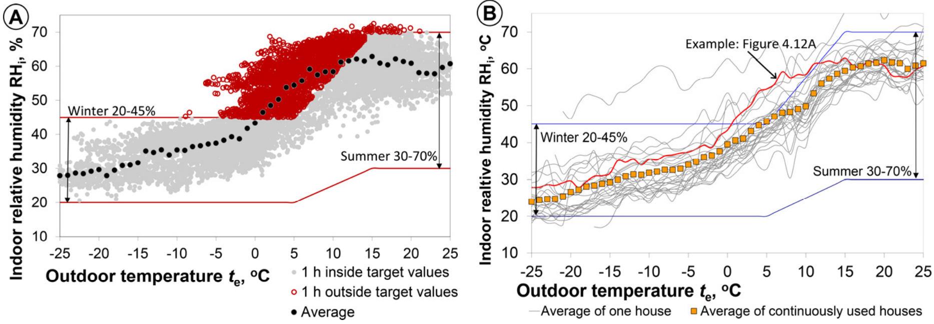


Figure 4.12. Dependence of the indoor *RH* on the t_e in one house (A) and in all continuously used houses (B).

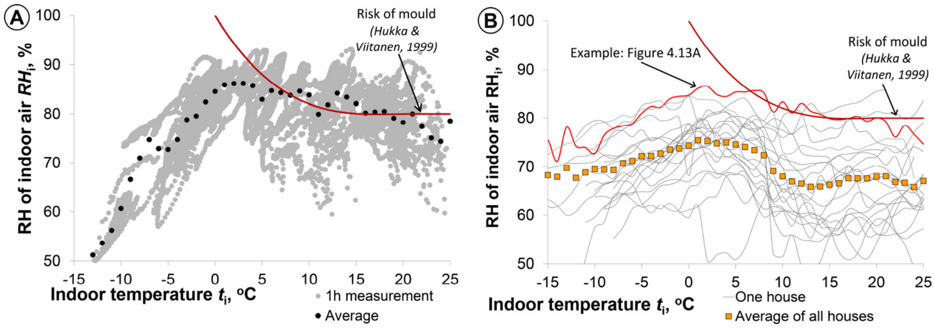


Figure 4.13. Dependence of the indoor *RH* on the t_i and risk of mould growth in one house (A) and in all unheated houses (B).

The temperature of the inner surface of the joint of the external wall and the base floor was measured in 30 houses. The *RH* and the *M* on that surface were calculated taking into account the indoor air *MC* (Figure 4.14B). Of the measured houses 27% (five houses) had mould growth risk, among them three continuously used houses and two unheated houses. The risk was mainly caused by a thermal bridge or air leakage.

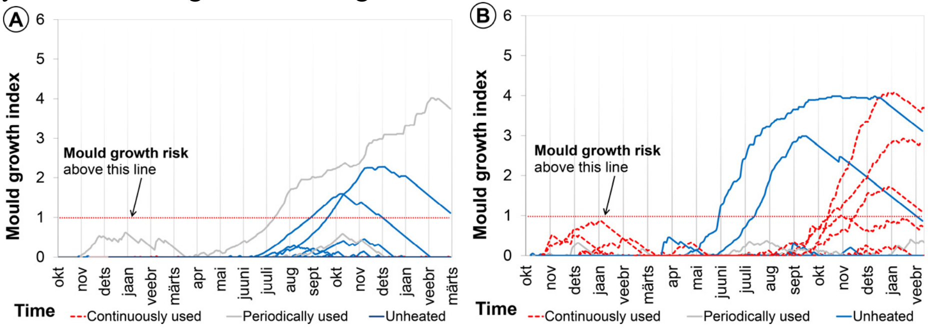


Figure 4.14. The level of *M* in the indoor air (A) and at the inner surface of the joint of the external wall and the base floor (B) in continuously used, in periodically used/heated and in unheated houses.

The stability of the indoor *RH* is important because historic houses may contain valuable interior and wooden objects. The average daily variation of the indoor *RH* is 5–6% in houses continuously used all year round (Figure 4.15A), which means that it is not related to outdoor climate. In unheated houses, the average daily variation of the indoor *RH* is 2–5%, i.e. about two times lower during the wintertime than in heated houses (Figure 4.15B). Comparison of the summer and the winter period showed that during summer the average variation of the indoor *RH* was 0.5–2.9% higher ($p = 7\times10^{-7}$ in unheated houses).

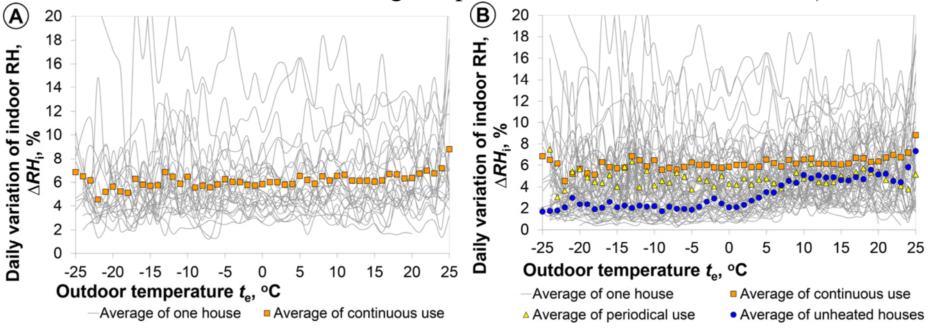


Figure 4.15. Average daily variation of the indoor *RH* in continuously used houses (A) and in all houses with different usage profiles (B) as a function of t_e.

The average daily *RH* variation stayed almost always below 10%: being on average 2.1–6.0% during winter and 5.0–6.5% during summer (Figure 4.15). According to a previous study (Brown et al., 2002), there is a low risk of damage to most organic materials (in only a couple of cases it can be dangerous to some composite materials) caused by swelling and shrinkage due to the variation of *RH* in naturally ventilated historic rural houses.

4.2.3 Indoor humidity loads

The internal moisture excess was selected as the main parameter of indoor humidity loads. Comparison of the houses based on their usage profile showed that during the winter period the highest average moisture load was in continuously used houses (2.8 g/m^3), medium in periodically used houses (1.2 g/m^3) and the lowest load in unused houses (0.2 g/m^3) (Figure 4.16A). All differences were significant: between continuously used and periodically used houses $p = 2\times10^{-7}$, between periodically used and unused houses $p = 4\times10^{-3}$ and between continuously used and unused houses $p = 4\times10^{-16}$. During the summer period the moisture excess was similar at all house usage profiles (0–1 g/m^3). Figure 4.16B shows a 10% higher critical level, which means that hygrothermal loads higher than the determined critical value should not exceed 10% of the cases.

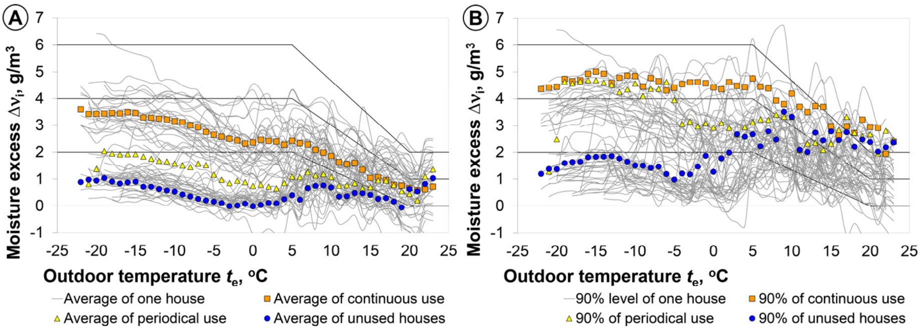


Figure 4.16. Weekly average (A) and 90% level (B) of moisture excess in all measured houses according to the usage profile. The horizontal straight lines represent high (starting from 6) and low (starting from 4) moisture excess design values (90 % level) based on previous studies in Estonian houses.

4.3 Air leakage and infiltration

4.3.1 Airtightness of the building envelope and air leakage locations

To compare the airtightness of different buildings, the air flow rate at the pressure difference ±50 Pa was divided by the external envelope area (resulting air leakage rate at ±50 Pa, q_{50}-value) or by the internal volume of the building (resulting ACH at 50 Pa, n_{50}-value). The results of air leakage rate and ACH at ±50 Pa from fan pressurisation measurements are presented in Figure 4.17.

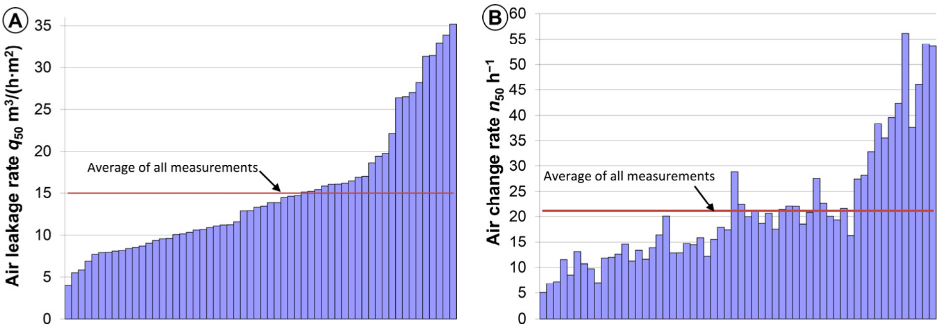


Figure 4.17. Air leakage rate (A) and ACH (B) in all measured houses.

According to Figure 4.18A, there was almost no significant difference in the airtightness of building envelopes depending on the age of the building. Based on 58 measurements, the airtightness of rural houses made of logs has not changed during two centuries: q_{50} = 15 m^3/(h·m^2) (values between 3.9 and 35 m^3/(h·m^2)); mean ACH was n_{50} = 21 h^{-1} (values between 5.1 and 56 h^{-1}).

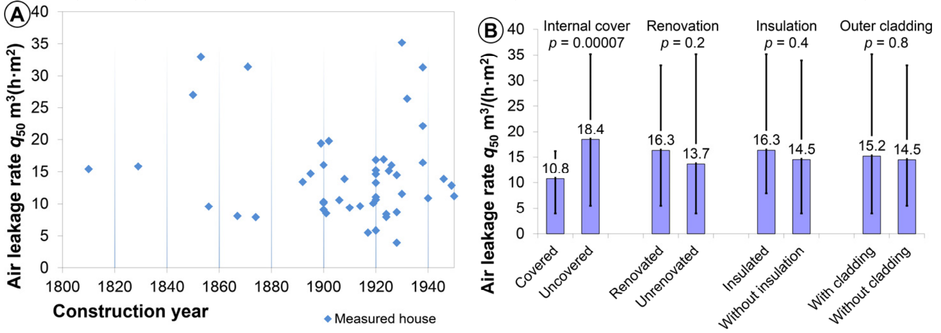


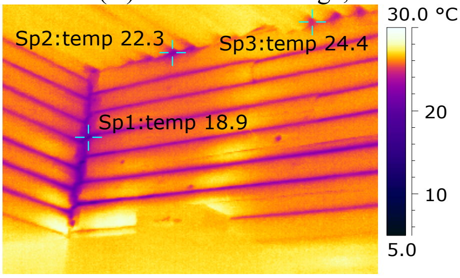
Figure 4.18. Correlation of air leakage rate and construction year (A) in all measured houses. Air leakage rate depending on selected characteristics of the envelope (B) in the measured houses.

Among the compared characteristics of the building envelope the internal covering of the external wall has the most significant influence on the airtightness of the building envelope (Figure 4.18B). In almost half of the houses the external walls were covered with a layer of plaster or plywood on the inside. The houses where the external walls were covered on the inside had a 25% lower air leakage rate than other houses. Among an equal number of renovated and unrenovated houses (the house was considered as renovated when substantial renovations had been performed on it during the past 20 years), there was no influence of renovation works on the building's air leakage. There was also no difference between the air leakage of the houses where external wooden wall cladding was present (2/3 of the houses had external cladding, sometimes with sheathing paper on the log surface) or the houses that were additionally insulated (1/4 of the houses were additionally insulated).

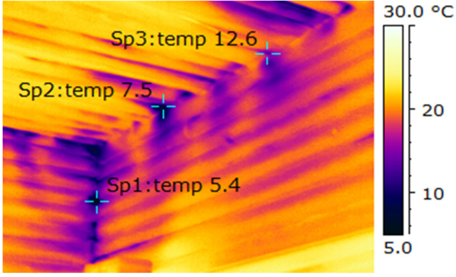
To determine typical locations of air leakage and their distribution, an infrared image camera was used. Figure 4.19 and Figure 4.20 present examples of air leakage locations on the junction of the ceiling and the external wall.

Typical air leakage places in the studied houses were

- junction of the ceiling with the external wall (33%);
- junction of the floor with the external wall (14%);
- envelope surface (mainly cracks between logs) (20%);
- junction of external walls (9%);
- leakage around and through windows and doors (21%).


(A) Thermocam image, ±0 Pa


(C) Photo


(B) Thermocam image, −50 Pa

Outdoor temperature	+1.5 °C
Indoor temperature	+27.1 °C
Measured surface temperatures	
Sp1 (±0 Pa)	18.9 °C
Sp2 (±0 Pa)	22.3 °C
Sp3 (±0 Pa)	24.4 °C
Sp1 (−50 Pa)	5.4 °C
Sp2 (−50 Pa)	7.5 °C
Sp3 (−50 Pa)	12.6 °C

Figure 4.19. Thermocam image from the junction of the external wall and the ceiling under normal conditions (A); thermocam image after 50 Pa depressure (B). Normal image (C) and numeric data (table).

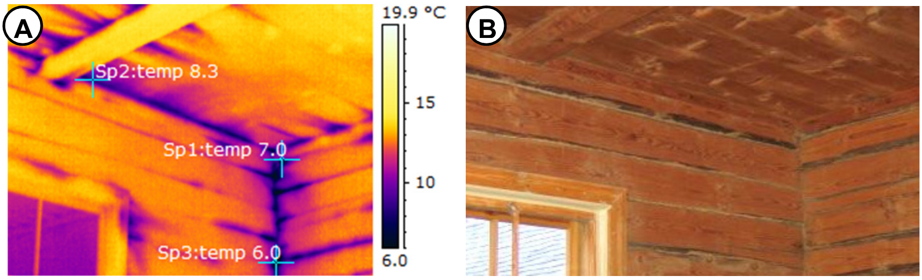


Figure 4.20. Air leakage in the junction of external walls and through cracks between logs; thermocam image (A) and photo (B).

4.3.2 Infiltration during normal house use

The measurement results are presented in paper VI (Table 1). The average ACH during normal house usage was 0.57 h^{-1} (the average value during summer and winter was the same). The minimum ACH was 0.16 h^{-1} (in summer) and the maximum ACH was 1.22 h^{-1} (in winter). The minimum and maximum values were measured in the same house at different times. Based on these measurements and other results, there is no direct correlation between the airtightness and natural infiltration of a house.

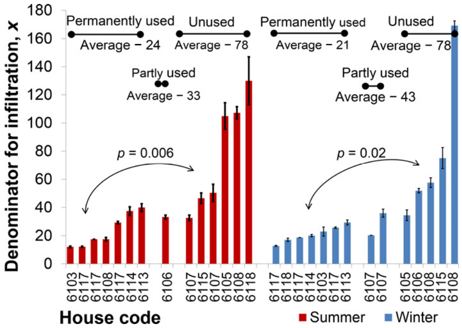


Figure 4.21. Passive infiltration in houses with a different usage profile in summer and winter.

A statistically significant difference was detected in passive infiltration between permanently used and unused houses (respectively $p = 0.006$ and $p = 0.02$ in summer and winter). The factor x is more than three times smaller in the permanently used houses than in the unused houses: natural infiltration is three times lower in the unused houses compared to the permanently used houses (Figure 4.21).

Outdoor temperature conditions influence air pressure conditions and therefore also the air leakage rate. Nevertheless, seasons have a smaller impact on the air leakage than house usage: average values were $x = 24$ in summer and $x = 21$ in winter in permanently used houses; in unused houses $x = 78$ both in summer and in winter.

4.4 Interior thermal insulation of log walls

4.4.1 Validation of the calculation model

The calculation model was validated by choosing the materials best matching those used in the measured structure from the default WUFI database and by slightly modifying the default material properties according to information found in the literature. The wood material used in the model for logs was defined in the WUFI database as ‘Scandinavian spruce transverse direction II’, which takes into account the anisotropic properties of wood. Because the measured old log walls had a high leakage rate (Arumägi et al., 2015), air exchange through the log wall was added (air exchange was defined between the outdoor air and the mineral wool layer) to have a better match between measured and calculated values. The validation of the simulation model and field measurements was done by comparing measured and calculated temperatures (Figure 4.22A) and *RH* (Figure 4.22B) on the studied critical surface between mineral wool and log wall layers. There was a good correlation between measured and calculated results.

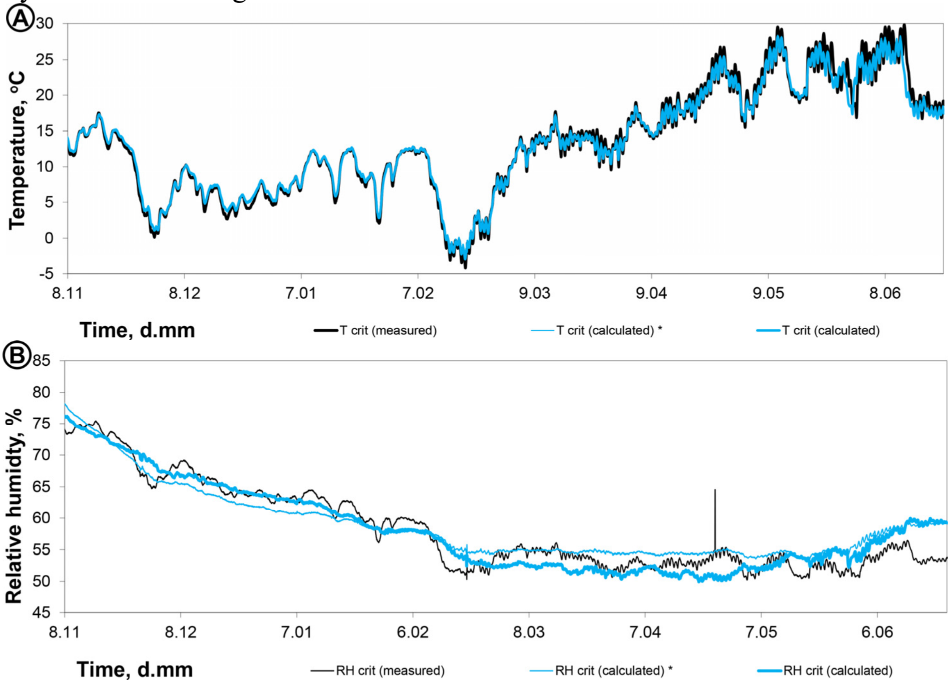


Figure 4.22. Comparison of the measured and calculated temperature (A) and *RH* (B) on the studied critical surface between mineral wool and log wall layers (Figure 3.2). Calculated temperature and *RH* marked with an asterisk represent the calculation case where air leakage was excluded.

4.4.2 Parametric study

Effect of the time of starting renovation works

Based on our experience, homeowners often start major renovation works in spring or early summer (May to June) because the weather is more convenient for builders. In case of a continuously heated house, when only interior insulation works are planned, the outdoor climate (and therefore the preferred season for insulation works) is irrelevant. Figure 4.23 presents the average *MC* in stipulated log layers (based on Figure 3.2) from the start of renovation: each line represents the average *MC* at a given depth from 12 simulations. The *MC* curves for each of the months mainly overlap.

The highest fluctuation in moisture levels in an unheated house occurs in the outer layer (layer 1): from 12% in May to 17% in February (Figure 4.23A). In a heated house, the *MC* is only by up to 0.5% lower during winter (Figure 4.23B).

A 30 mm thick layer next to the outer layer (layer 2) has a significantly lower *MC* fluctuation: from 13% in August to 17% in March (Figure 4.23A). In the central layer (layer 3), moisture levels are the most stable fluctuating from 13% in autumn to 14% in spring (Figure 4.23A). The *MC* in layers 2 and 3 in a heated house is slightly higher during winter (Figure 4.23B). The *MC* in layer 4 is 1% lower than that in layer 3 during spring and summer but similar during autumn and winter months (Figure 4.23). The innermost layer (layer 5) shows higher fluctuation and the highest difference between an unheated and a heated house. The *MC* in layer 5 ranges from 11% in summer to 14% in spring. During the winter, the *MC* in layer 5 is 11% in a heated house and 13% in an unheated house. It may be concluded that the average *MC* in a log wall (Figure 4.23) is the lowest during summer months (minimum 13% in July) and the highest during winter months (maximum over 14% in February). Diffusive moisture transport in wood is a slow process, as the time interval between the peak points in the surface layer and in the middle layer is at least three months. This means that the diffusive moisture flux takes at least six months to penetrate a 150 mm thick log wall.

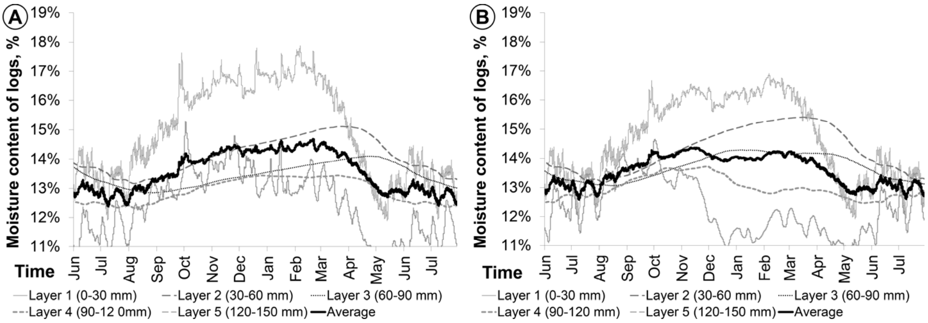


Figure 4.23. The *MC* in log layers (Figure 3.2) in an unheated house (A) and a continuously heated house (B).

The maximum *M* values on the critical surface were below 1 in all the previously calculated months in both heated and unheated houses. It is safe to install an internal insulation layer all year round but it is safer from May to August when the average *MC* of the wall is lower. This also matches owners' renovation time preferences.

Drying-out of built-in moisture

The drying-out potential of an interiorly insulated log wall in an unheated and in a heated house over the course of five years is shown in Figure 4.24. In the absence of a special water vapour barrier, the wall of an unheated house with a low Δv_i will dry to 14%−15% in two years (Figure 4.24C). If a wall structure without a vapour barrier is in a heated house Δv_i = 5/1.5 g/m^3, the *MC* will keep rising over the course of years. With an average vapour barrier (used in the RC) in a wall structure, the wall keeps drying in both heated and unheated houses (Figure 4.24A). In an unheated house, Δv_i is lower, and therefore after five years the *MC* there (14%−15%) is 1% lower than in a heated house (15%−16%) with a higher Δv_i. With a very vapour-tight barrier (Figure 4.24D), drying takes longer, and the influence of Δv_i is insignificant. In a heated house, drying is faster, and after five years, the *MC* is about 13% and in an unheated house, between 14% and 15%.

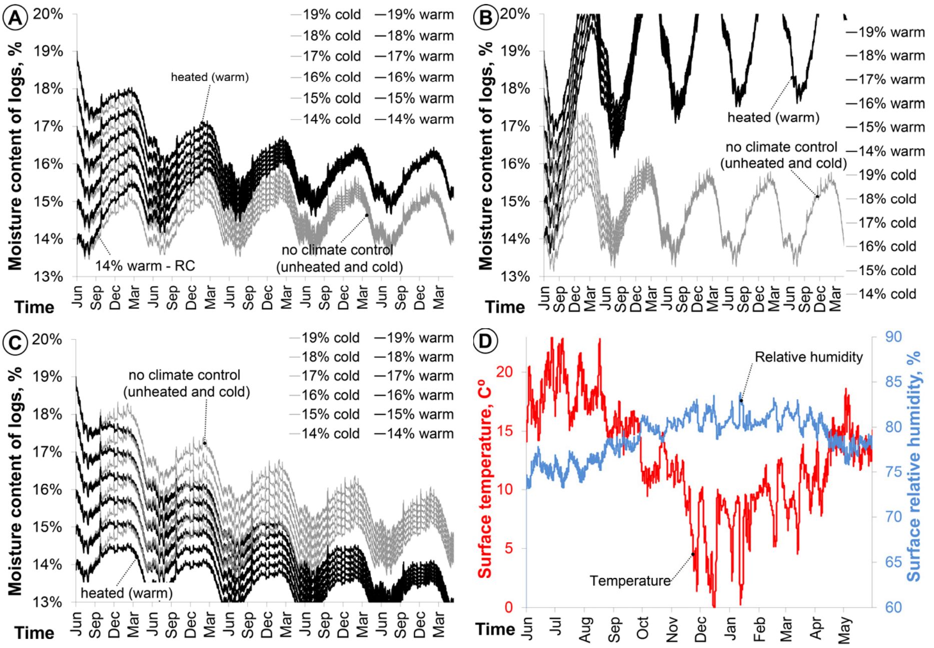


Figure 4.24. Change of the average *MC* in logs during a five-year period in unheated (cold) and heated (warm) houses with the reference vapour barrier – $S_d = 2$ m (A), without the vapour barrier (B) and a very vapour-tight barrier – $S_d = 100$ m (C). Temperature and *RH* on the inner surface of a log in a heated house (RC) (D).

In a heated house, moisture levels in the inner layer decrease faster; in the middle layer, however, no significant difference was found between a heated and an unheated house. It takes at least two times longer to dry a log wall interiorly insulated and covered with a vapour-tight barrier than to dry a log wall without any insulation. If at the beginning the built-in moisture level is 14%, it will not decrease in a cold house in one year; rather, it will increase during winter. When moisture levels are higher at the beginning, the decrease will also be higher during the first few months (summer months). In spring (from March), moisture levels decrease in all cases.

Figure 4.24D presents the surface temperature and relative humidity curves at the critical point in the wall (see Figure 3.2) throughout the year as calculated under the conditions of RC. This figure also confirms lower moisture levels and higher temperatures during summer, resulting in a lower mould growth risk.

A single-parameter study of mould risk on the inner surface of a log wall

Figure 4.25 and Figure 4.26 present the mould index, depending on time, over the course of five years. The red dotted line shows below which safe values occur.

The initial moisture of a log may be the dominant moisture source for an interiorly insulated log wall, in particular when the interior insulation is covered with a tight vapour barrier. The *MC* of 14% may be considered acceptable, whereas a higher level causes *M* values over 1; even though *M* at 15% *MC* remains below 1 during three years, it will exceed the limit during the fourth year (Figure 4.25A). The *MC* over 15% is definitely unacceptable because the mould growth will begin in less than half a year, and it is not relevant when the wall has finally dried out or when mould growth stops.

Figure 4.25B illustrates the need for a good vapour barrier. Barriers with small $S_d = 0.01$ m (no special vapour barrier, just gypsum board) and $S_d = 0.1$ m (range of bitumen-coated building paper) did not protect the wall construction from indoor moisture excess and heavy mould growth can be expected inside the wall. Neither did smart vapour barriers with $S_d \approx 1$ m protect against mould growth inside the wall, although the growth was slower. The minimum S_d of the vapour barrier is 2 m in the RC with a rather high Δv_i. Vapour barriers with a higher $S_d = 10$ m (similarly to laminated construction paper) and $S_d = 100$ m (range of plastic polyethylene sheeting) are well suited in these conditions.

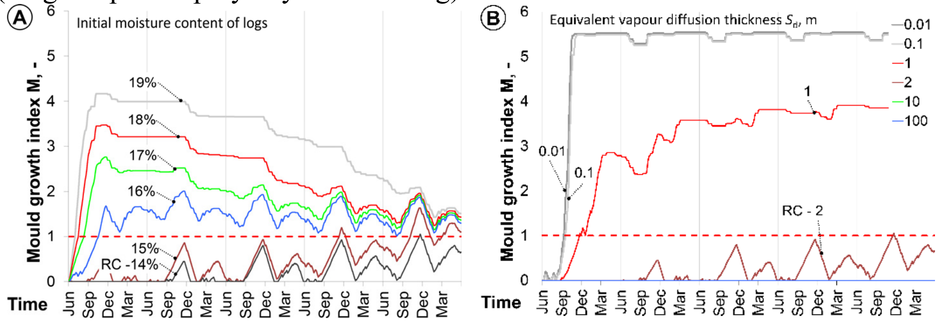


Figure 4.25. The level of *M* between the inner surface of a log and insulation depending on the initial moisture level of logs (A) and on the S_d of the water vapour membrane (B).

If a completely vapour-tight water vapour barrier material like plastic polyethylene sheeting is not used, then the interior insulation thickness can have a significant effect on mould growth inside the wall (Figure 4.26A). In RC a better version of a smart vapour retarder membrane was used and then varying the thickness of the insulation layer showed that *M* would increase with increasing thickness: a thickness of 50 mm may be considered as the maximum, while 75 mm is unacceptable. The insulation layer thickness has a greater effect on *M* than the thickness of the log wall: the minimum thickness of the wall should be 150 mm (Figure 4.26B). The thermal resistance of a mineral wool layer of 50 mm with a covering gypsum board (additional insulation with finishing layers) equals 1.3 (m^2·K)/W. The thermal resistance of a log wall (the present external wall) with a thickness of 150 mm equals 1.2 (m^2·K)/W. In order to avoid mould growth risk, the maximum thermal resistance of additional insulation with finishing layers should be almost equal to the minimum thermal resistance of the present external wall if only the thickness of additional thermal insulation is changed compared with the RC.

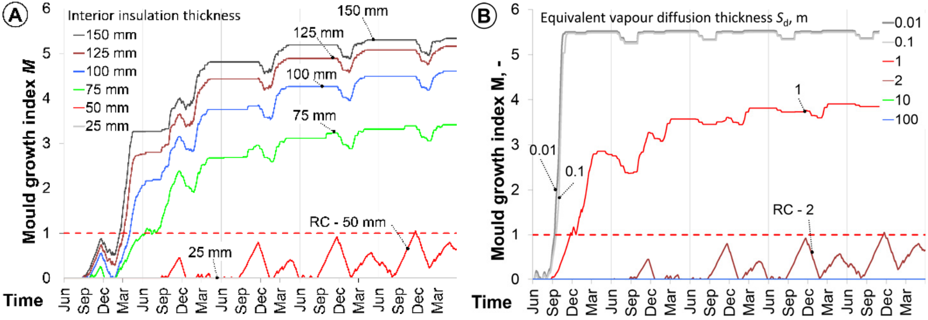


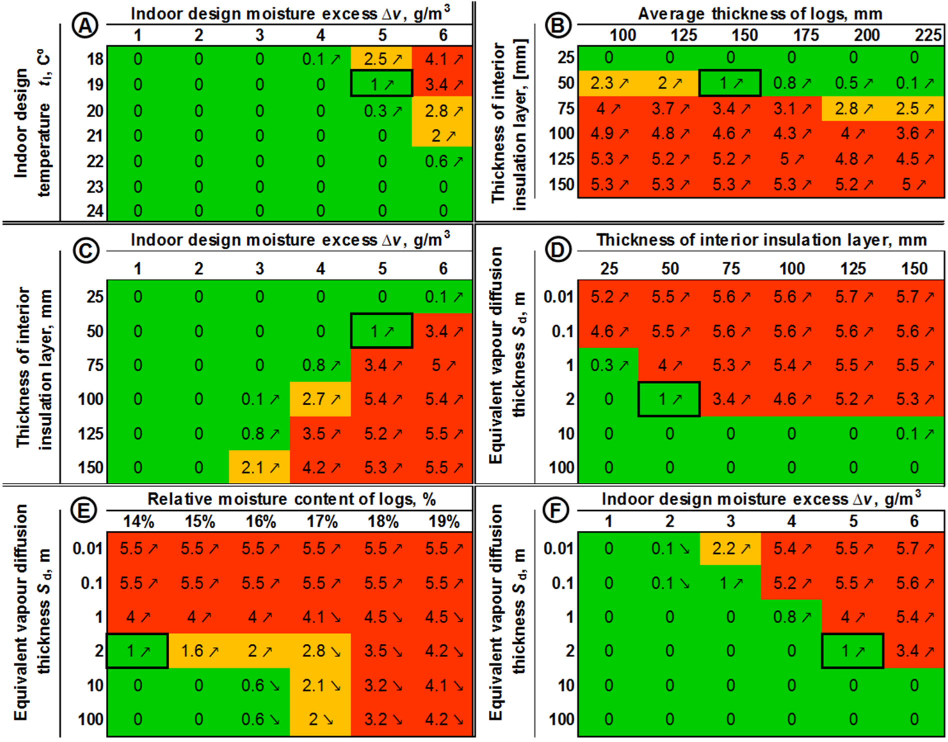
Figure 4.26. Variation of *M* over five years on the inner surface of a log depending on the interior insulation layer thickness (A) and the log wall thickness (B).

Mould risk with multiple varying parameters

Previously, only one parameter of the RC was varied. To study this rather complex case, two or three parameters of the RC were varied. The following table-like figures (Figure 4.27 and Figure 4.28) present the maximum *M* on the critical surface of a wall from our five-year calculation.

Generally speaking, each of the six parameters compared has a smaller or greater effect on the temperature and *RH* level of a wall on the critical surface studied. Increasing the indoor humidity load or decreasing the vapour diffusion thickness of the vapour barrier increases the moisture diffusion rate from indoors to outdoors through the wall, increasing the *RH* on the critical surface. Increasing the indoor temperature or the thickness of the log wall increases the temperature and decreases the *RH* on the critical surface. Increasing the thickness of an additional insulation layer decreases the temperature and increases the *RH* on the critical surface. Decreasing the initial *MC* of logs also decreases the moisture diffusion rate from logs to indoors, decreasing the *RH* on the critical surface.

Decreasing the Δv_i by 1 g/m^3 has a greater impact on avoiding mould growth risk than increasing the average indoor temperature by 1 °C (Figure 4.27A). The maximum acceptable level was found to be $\Delta v_i = 5$ g/m^3. Decreasing the interior insulation thickness has a bigger effect than increasing the thickness of the log wall (Figure 4.27B). A thin insulation layer of 25 mm may be considered safe even at a very high $\Delta v_i = 6$ g/m^3 (Figure 4.27C); at $\Delta v_i = 5$ g/m^3, with a maximum insulation thickness of 50 mm, as in the RC, is acceptable. When a low $\Delta v_i = 3$ g/m^3 is guaranteed, the insulation thickness may be up to 150 mm. The effect of $\Delta v_i = 1$ g/m^3 on avoiding mould growth risk is higher than the effect of decreasing the interior insulation thickness of 25 mm Figure 4.27C). Another possibility of using a thicker insulation layer is to install a vapour barrier with a high $S_d \geq 10$ m (Figure 4.27D). When the S_d and *MC* of logs were compared (Figure 4.27E), it was found that the S_d must be over 2 m or, rather, over 10 m if there is a risk of *MC* being over 14% in logs. The effect of a vapour barrier seems to be more important than the *MC* of logs. If $\Delta v_i = 3$ g/m^3 (Figure 4.28A), up to 16% of the initial *MC* of logs may be acceptable and a wider range of vapour barriers may be used. A higher Δv_i should be coupled with a better vapour barrier, i.e. with a higher S_d (Figure 4.27F). There is no acceptable combination where the relative *MC* of logs is over 17% whilst a good vapour barrier (with $S_d > 10$ m) is used: excessive mould growth is expected in a house with a high or low Δv_i (Figure 4.27E or Figure 4.28A) or even in a cold house with $\Delta v_i \approx 0$ g/m^3 (Figure 4.28B). Therefore, it is unacceptable to cover logs having an excessively high *MC* with a vapour-tight barrier.



Ⓐ	Indoor design moisture excess Δv, g/m³					
Indoor design temperature t_{I}, C°	1	2	3	4	5	6
18	0	0	0	0.1 ↗	2.5 ↗	4.1 ↗
19	0	0	0	0	1 ↗	3.4 ↗
20	0	0	0	0	0.3 ↗	2.8 ↗
21	0	0	0	0	0	2 ↗
22	0	0	0	0	0	0.6 ↗
23	0	0	0	0	0	0
24	0	0	0	0	0	0

Ⓑ	Average thickness of logs, mm					
Thickness of interior insulation layer, [mm]	100	125	150	175	200	225
25	0	0	0	0	0	0
50	2.3 ↗	2 ↗	1 ↗	0.8 ↗	0.5 ↗	0.1 ↗
75	4 ↗	3.7 ↗	3.4 ↗	3.1 ↗	2.8 ↗	2.5 ↗
100	4.9 ↗	4.8 ↗	4.6 ↗	4.3 ↗	4 ↗	3.6 ↗
125	5.3 ↗	5.2 ↗	5.2 ↗	5 ↗	4.8 ↗	4.5 ↗
150	5.3 ↗	5.3 ↗	5.3 ↗	5.3 ↗	5.2 ↗	5 ↗

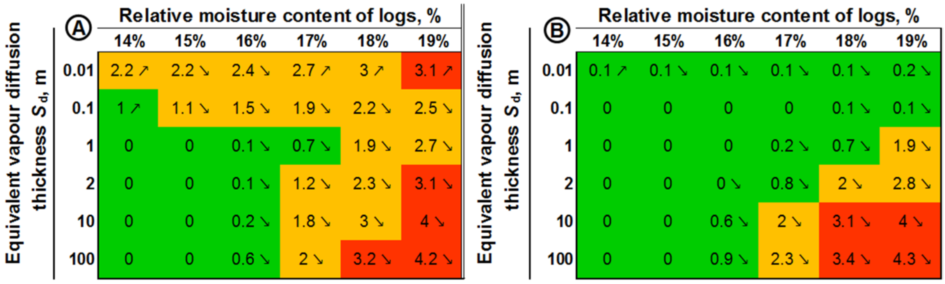
Ⓒ	Indoor design moisture excess Δv, g/m³					
Thickness of interior insulation layer, mm	1	2	3	4	5	6
25	0	0	0	0	0	0.1 ↗
50	0	0	0	0	1 ↗	3.4 ↗
75	0	0	0	0.8 ↗	3.4 ↗	5 ↗
100	0	0	0.1 ↗	2.7 ↗	5.4 ↗	5.4 ↗
125	0	0	0.8 ↗	3.5 ↗	5.2 ↗	5.5 ↗
150	0	0	2.1 ↗	4.2 ↗	5.3 ↗	5.5 ↗

Ⓓ	Thickness of interior insulation layer, mm					
Equivalent vapour diffusion thickness S_d, m	25	50	75	100	125	150
0.01	5.2 ↗	5.5 ↗	5.6 ↗	5.6 ↗	5.7 ↗	5.7 ↗
0.1	4.6 ↗	5.5 ↗	5.6 ↗	5.6 ↗	5.6 ↗	5.6 ↗
1	0.3 ↗	4 ↗	5.3 ↗	5.4 ↗	5.5 ↗	5.5 ↗
2	0	1 ↗	3.4 ↗	4.6 ↗	5.2 ↗	5.3 ↗
10	0	0	0	0	0	0.1 ↗
100	0	0	0	0	0	0

Ⓔ	Relative moisture content of logs, %					
Equivalent vapour diffusion thickness S_d, m	14%	15%	16%	17%	18%	19%
0.01	5.5 ↗	5.5 ↗	5.5 ↗	5.5 ↗	5.5 ↗	5.5 ↗
0.1	5.5 ↗	5.5 ↗	5.5 ↗	5.5 ↗	5.5 ↗	5.5 ↗
1	4 ↗	4 ↗	4 ↗	4.1 ↘	4.5 ↘	4.5 ↘
2	1 ↗	1.6 ↗	2 ↗	2.8 ↘	3.5 ↘	4.2 ↘
10	0	0	0.6 ↘	2.1 ↘	3.2 ↘	4.1 ↘
100	0	0	0.6 ↘	2 ↘	3.2 ↘	4.2 ↘

Ⓕ	Indoor design moisture excess Δv, g/m³					
Equivalent vapour diffusion thickness S_d, m	1	2	3	4	5	6
0.01	0	0.1 ↘	2.2 ↗	5.4 ↗	5.5 ↗	5.7 ↗
0.1	0	0.1 ↘	1 ↗	5.2 ↗	5.5 ↗	5.6 ↗
1	0	0	0	0.8 ↗	4 ↗	5.4 ↗
2	0	0	0	0	1 ↗	3.4 ↗
10	0	0	0	0	0	0
100	0	0	0	0	0	0

Figure 4.27. Dependence of *M* between the inner surface of a log and insulation on indoor design temperature and Δv_i (A), thickness of an interior insulation layer and thickness of a log wall (B), Δv_i and thickness of an interior insulation layer (C), S_d of a vapour barrier and thickness of an interior insulation layer (D), S_d of a vapour barrier and relative *MC* of logs (E), S_d and indoor moisture excess (F). RC is presented in the square outlined in bold. The symbols ↘ and ↗ indicate the *M* trend from year 2 to year 5 against year 1 (lower or higher, respectively).



Ⓐ

Equivalent vapour diffusion thickness S_d, m	Relative moisture content of logs, %					
	14%	15%	16%	17%	18%	19%
0.01	2.2 ↗	2.2 ↘	2.4 ↘	2.7 ↗	3 ↗	3.1 ↗
0.1	1 ↗	1.1 ↘	1.5 ↘	1.9 ↘	2.2 ↘	2.5 ↘
1	0	0	0.1 ↘	0.7 ↘	1.9 ↘	2.7 ↘
2	0	0	0.1 ↘	1.2 ↘	2.3 ↘	3.1 ↘
10	0	0	0.2 ↘	1.8 ↘	3 ↘	4 ↘
100	0	0	0.6 ↘	2 ↘	3.2 ↘	4.2 ↘

Ⓑ

Equivalent vapour diffusion thickness S_d, m	Relative moisture content of logs, %					
	14%	15%	16%	17%	18%	19%
0.01	0.1 ↗	0.1 ↘	0.1 ↘	0.1 ↘	0.1 ↘	0.2 ↘
0.1	0	0	0	0	0.1 ↘	0.1 ↘
1	0	0	0	0.2 ↘	0.7 ↘	1.9 ↘
2	0	0	0 ↘	0.8 ↘	2 ↘	2.8 ↘
10	0	0	0.6 ↘	2 ↘	3.1 ↘	4 ↘
100	0	0	0.9 ↘	2.3 ↘	3.4 ↘	4.3 ↘

Figure 4.28. Dependence of *M* between the inner surface of a log and insulation: S_d and relative *MC* of logs at lower Δv_i = 3 g/m^3 during winter (A) or in an unheated house at Δv_i = 0.5 g/m^3 (B). The symbols ↘ or and ↗ indicate the *M* trend from year 2 to year 5 against year 1 (lower or higher, respectively).

Selection of a suitable vapour barrier

Selection of a suitable vapour barrier for an unheated house (cold and unused during winter) is explained in Figure 4.29 by comparing the *M* of heated and unheated houses with *MC* levels in log walls of 16% or 17% (rather high *MC* was chosen for graphical reasons in order to visualise the difference). The vapour barrier in a heated house should have S_d > 10 m in case of the selected *MC* and at least 2 m when the relative *MC* of logs is up to 14% (Figure 4.27E). In unheated houses, S_d = 2 m is the maximum acceptable level (Figure 4.28B) when logs have a *MC* above 17% at the time of insulation.

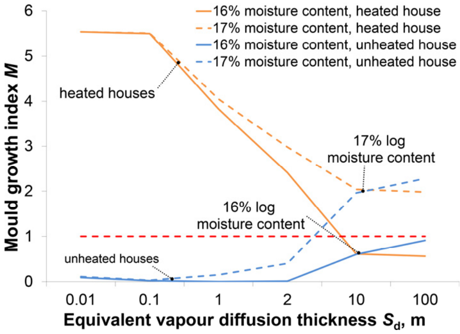


Figure 4.29. Relation between the *M* and the S_d of a vapour barrier in heated and unheated houses.

4.4.3 Materials for interior insulation

Different combinations of the described parameters were calculated with the simulation software WUFI.

The initial moisture of a log can be the dominant moisture source for an interiorly insulated log wall, in particular when the assembly is equipped with a vapour barrier. Figure 4.30 presents the values of *M* for all three insulation materials when the initial moisture level was varied (the other parameters according to the RC). The wall with reed mat insulation is able to dry out to both sides (indoors and outdoors), this insulation material has some moisture storage properties and is not covered with a water vapour-tight layer on the inner side. Therefore, this wall has the highest acceptable initial *MC* of the log. As the cellulose fibre is installed by a wet spray method, it brings additional moisture to the assembly. Therefore, the cellulose fibre insulation layer needs to stay open at least for a week before it is covered with a water vapour barrier and a gypsum board. After covering that assembly with a water vapour barrier, the constructional moisture can dry out only to outdoors. This assembly accepts a measured initial *MC* of up to 15% for a log wall when the insulation layer has dried at least for a week in a heated and continuously ventilated room before covering. When the insulation is covered with a water vapour barrier just after installation or the room is unheated or not continuously ventilated, the acceptable measured initial moisture level is 12%. The acceptable measured *MC* of logs with mineral wool insulation is up to 14%. Even though mineral wool itself is dry, its moisture storage capability is about 10 times lower than of cellulose fibre.

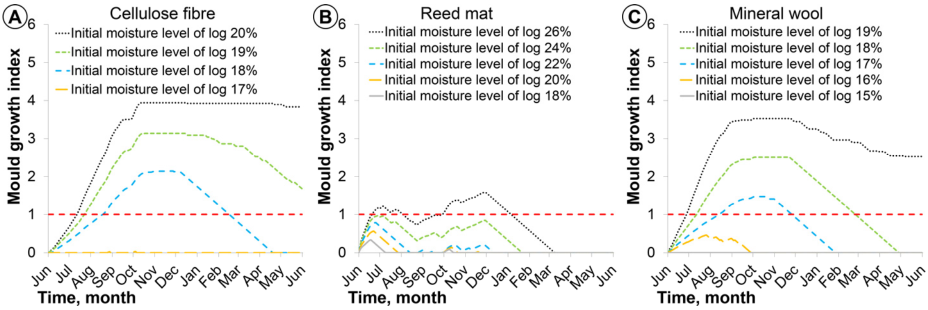


Figure 4.30. Dependence of *M* on the inner surface of a log in contact with cellulose fibre (A), reed mat (B) and mineral wool (C) on the initial moisture level of logs. The red dotted line marks *M* level 1 below which safe values occur (combinations).

A high *MC* is especially critical when the assembly is equipped with a vapour barrier on the inner surface of the insulation. Figure 4.31 shows walls with cellulose fibre insulation (A) and mineral wool (B) with different resistances of the vapour barrier and the calculated initial *MC* of 17% in logs. Use of membranes with high water vapour resistance (polyethylene membrane and smart vapour retarder membrane) resulted in a high mould growth risk when the covered insulation was wet cellulose fibre. In both cases the use of laminated paper resulted in the lowest mould growth levels. The solution without a vapour barrier was not on the safe side in either case, although the mould growth level was lower with cellulose fibre, probably because of its higher moisture buffering capacity. When both the log wall and the insulation layer have dried out, it is safe to cover them with either a polyethylene membrane or a smart vapour retarder membrane (Figure 4.31B).

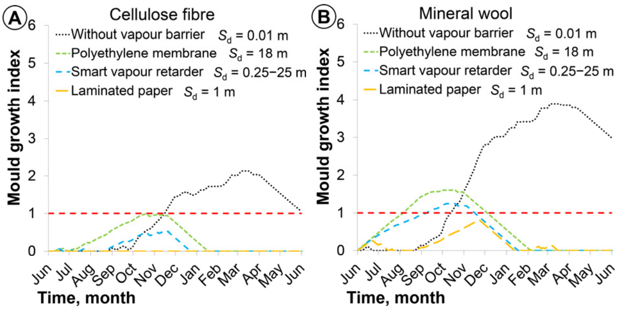


Figure 4.31. The dependence of water vapour resistance of a vapour barrier on the *M* on the inner surface of the log in contact with cellulose fibre (A) and mineral wool (B). The red dotted line marks *M* level 1 below which safe values occur (combinations).

The thickness of the log influences the hygrothermal performance of the wall due to different constructional moisture of the log and the thermal and vapour resistance on the exterior side of the insulation. However, the impact of the thickness of the logs on the hygrothermal performance of an interiorly insulated log wall is rather small (Figure 4.32). A general understanding that a thicker wall with a 50 mm additional insulation layer is hygrothermally safer is valid only in the case of reed mat insulation. The inwards drying is limited with the interior vapour barrier (walls with cellulose fibre and mineral wool). A thicker wall has a higher thermal resistance and therefore the interior surface temperature will increase and the *RH* will decrease. The increase of the interior surface *RH* caused by a larger amount of drying water in a thicker log will dominate the small *RH* decrease from the higher thermal resistance of the thicker wall. As the measured *MC* of logs of 15% (RC) is too high for the use of cellulose fibre, the *M* of both a 100 mm and a 200 mm thick wall is high. In contrast, when the wall is insulated with mineral wool, $M < 1$ in case of both thicknesses.

Varying the thickness of the insulation layer (Figure 4.33) shows that increasing the thickness will increase *M*. The impact of the insulation layer thickness on *M* is higher than that of the thickness of the log wall. Even a 50 mm thick layer of cellulose fibre has $M > 1$, but the shape of the curve is similar to that of mineral wool insulation. It is safe to use a 70 mm thick reed mat, a 50 mm thick mineral wool and a 50 mm thick cellulose fibre insulation layer if the cellulose fibre is dried out before covering it with an optimal water vapour barrier (laminated paper). The results are sensitive to the water vapour resistance of the selected vapour barrier (Figure 4.31). Insulation thicknesses above the mentioned values can be possible only in certain conditions (dry thick log walls, low indoor humidity load, water vapour barrier with proper (calculated) vapour resistance).

When the log wall is covered with exterior boarding and protected from driving rain, the dominant humidity loads are from indoors and the log by diffusion.

Varying the indoor humidity load (Figure 4.34) showed that the highest acceptable indoor design moisture excess during winter (Δv) with reed mat insulation is 5 g/m^3.

The design moisture excess of 4 g/m^3 is acceptable with mineral wool and cellulose fibre (after drying out) interior insulation.

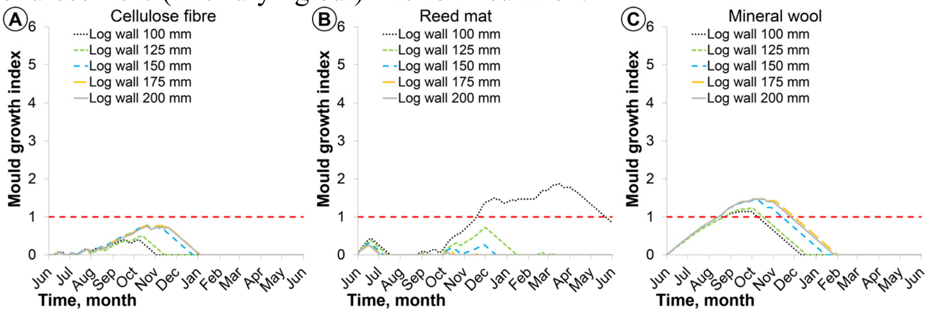


Figure 4.32. Dependence of *M* on the inner surface of the log in contact with cellulose fibre (A), reed mat (B) and mineral wool (C) on the thickness of the log wall. The red dotted line marks *M* level 1 below which safe values occur (combinations).

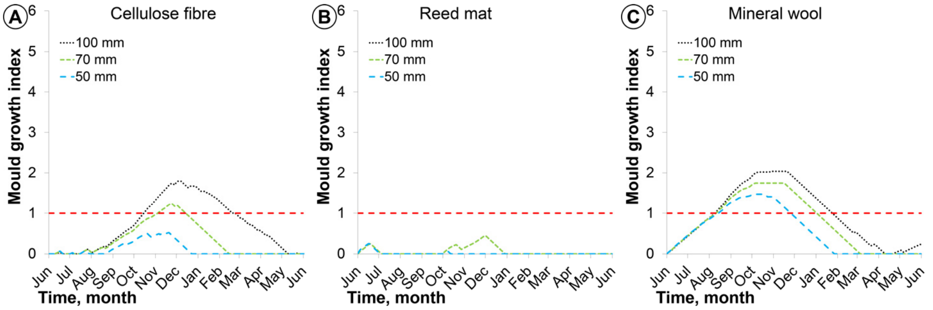


Figure 4.33. Dependence of *M* on the inner surface of the log in contact with cellulose fibre (A), reed mat (B) and mineral wool (C) depending on the thickness of the interior insulation layer. The red dotted line marks *M* level 1 below which safe values occur (combinations).

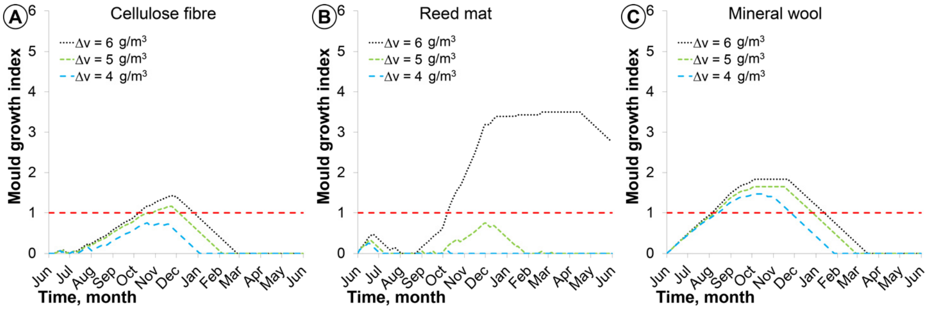


Figure 4.34. Dependence of *M* on the inner surface of the log in contact with cellulose fibre (A), reed mat (B) and mineral wool (C) on the indoor humidity load. The red dotted line marks *M* level 1 below which safe values occur (combinations).

4.5 Energy performance

4.5.1 Individual energy renovation measures

To show the influence of individual energy renovation measures on the sample building, the measures were added one by one to the sample house and their impact was calculated for standard building usage (see Table 4.1). The energy saving was compared with the base case (BC).

Table 4.1. Influence of individual energy renovation measures on the level and percentage reduction of annual delivered energy (DE, kW/(m^2·a)) and primary energy (PE, kW/(m^2·a))

Energy renovation measure	DE, kW/(m^2·a) / reduction from BC, %	PE, kW/(m^2·a) / reduction from BC, %
Original structures, no heat recovery for ventilation, old WS, DHW with electricity.		
BC: non-renovated / original ('as built') house	512 / ±0%	510 / ±0%
Improvement of indoor climate		
HR0: class II ventilation (without heat recovery)	535 / +4%	528 / +4%
Renovation of thermal envelope (no improvement of service systems)		
W1.6: old frame, new low-ε glasses and sealants	499 / −3%	500 / −2%
W1.1: new windows, outlook similar to original	490 / −4%	493 / −3%
W0.8: new windows, outlook similar to original	487 / −5%	491 / −4%
EW20: 20 mm sheathing	446 / −13%	460 / −10%
EW70: 50 mm insulation + 20 mm sheathing	409 / −20%	432 / −15%
EW120: 100 mm insulation + 20 mm sheathing	392 / −23%	420 / −18%
EW170: 150 mm insulation + 20 mm sheathing	376 / −27%	408 / −20%
EW220: 200 mm insulation + 20 mm sheathing	368 / −28%	402 / −21%
AF220: 200 mm insulation + 20 mm sheathing	455 / −11%	467 / −8%
AF420: 400 mm insulation + 20 mm sheathing	440 / −14%	456 / −11%
BF200: 200 mm insulation	464 / −10%	473 / −7%
BF300: 300 mm insulation	458 / −11%	469 / −8%
AT30: tightening of windows and building envelope	494 / −4%	497 / −3%
AT60: extremely careful tightening of windows and building envelope	472 / −8%	480 / −6%
Renovation of ventilation systems (no improvement of structures)		
VHR60: Class II ventilation (with 60% heat recovery)	462 / −10%	477 / −6%
VHR80: Class II ventilation (with 80% heat recovery)	442 / −14%	462 / −9%
Renovation of energy sources (no improvement of structures)		
WS: New or renovated wood burning stoves	417 / −19%	440 / −14%
WB: Wood burning boiler	459 / −10%	402 / −21%
WPB: Wood-pellet boiler	406 / −21%	362 / −29%

Energy renovation measure	DE, kW/(m^2·a) / reduction from BC, %	PE, kW/(m^2·a) / reduction from BC, %
OB: Oil condensate boiler	383 / −25%	408 / −20%
ER: Electrical radiators	316 / −34%	681 / +34%
AWHP: Air-water heat pump	174 / −66%	397 / −22%
AAHP: Air-air heat pump	245 / −52%	540 / +6%
GSHP: Ground source heat pump	129 / −75%	307 / −40%
SC: Solar collectors for DHW	485 / −5%	455 / −11%
PV: Photovoltaic panels	512 / 0%	503 / −1%

Implementing the required acceptable mechanical ventilation (ICC III) increases the energy consumption, but when the ventilation rate is further increased to ICC II (normal level of expectation for indoor climate) using a modern ventilation unit with heat recovery, then the *PE* can decrease by up to 9% compared to BC. Renovating or replacing old windows has a small influence on the overall energy consumption of a house; the reason is that the windows of old rural houses are rather small. These houses have a large external wall area; therefore insulating the external walls can decrease the *PE* by up to 21% when 200 mm insulation with 20 mm sheeting is added. Together with adding a thick insulation layer to the external walls the windows have to be moved to the same level as the insulation layer and sometimes also the roof needs to be replaced with a larger one (to have a similar length of eaves). This means that the insulating of the external walls is a complex and expensive work as compared with adding insulation to the attic floor, which is simple and decreases the *PE* by 11% when a 400 mm insulation layer is installed. Furthermore, insulating the attic floor does not change the visual appearance of the house.

The largest saving can be achieved with renovating heating systems starting with WS (*PE* decrease 14%) and up to the most effective heating system of GSHP (*PE* decrease 40%). SC covered 50% of the annual heating energy for DHW and PV covered 15% of the annual energy consumption for DHW.

4.5.2 Energy renovation packages

To achieve energy saving purposes, individual energy saving measures appear inadequate; a combination of different energy saving measures is needed. Renovation packages were calculated for different scenarios for different energy saving levels (Table 4.2).

The appearance of the building could have minimal changes when only the building service systems (heating and ventilation system, energy source) are improved. Merely the improvement of the ventilation system (VHR80) and the use of the best energy source (GSHP) can improve the energy performance by close to 50% of the DE:

PE = 273 kWh/(m^2·a) (−46%); *DE* = 112 kWh/(m^2·a) (−78%) (GSHP used).

Table 4.2. Energy renovation packages for different energy saving levels and countries

Energy saving level and renovation package		Delivered energy, kWh/(m^2·K) / decrease from BC, %	Primary energy, kWh/(m^2·a) / decrease from BC, %	Energy renovation measures														Energy source				
				Windows			External walls					Attic floor		Base floor		Ventilation						
				W1.6	W1.1	W0.8	EW20	EW70	EW120	EW170	EW220	AF220	AF420	BF200	BF300	VHR60	VHR80	WS	WPB	GSHP	SC	PV
I	−20% (PE)	355 / −31%	397 / −22%	×									×				×					
II		355 / −31%	398 / −22%	×			×					×		×								
III		363 / −29%	403 / −21%													×		×				
I	−60% (PE)	75 / −85%	199 / −61%	×								×		×			×			×	×	
II		124 / −76%	189 / −63%		×					×			×	×			×				×	
III		75 / −85%	199 / −61%										×	×			×			×	×	
I	−80%* (−88%**) (DE) max	40 / −92%	122 / −76%			×					×		×		×		×			×	×	×
II		109 / −79%	144 / −72%			×					×		×		×		×		×		×	
III		59 / −89%	159 / −69%	×			×					×		×			×			×	×	×

* Heating source other than electricity (wood, pellet, gas, oil).

** Heating source is electricity (direct electricity, heat pumps).

In package I with the target of minimal changes of the external appearance, a 20% *PE* reduction is easily achieved by insulating the attic floor (AF420) and using ventilation with 80% heat recovery (VHR80). In addition, the old windows need to be renovated. To achieve a 60% *PE* reduction in package I also the base floor insulation (BF200) and installation of the best energy source (GSHP and SC) are needed. As high as an 80% *PE* reduction cannot be achieved without insulating the external wall.

In package II, concentrating on the improvement of thermal comfort, the 20% *PE* reduction target is achieved with minimal insulation options of each envelope part. To achieve a 60% *PE* reduction, new windows (W1.1) and thicker insulation of the external walls are necessary (EW170) together with an efficient ventilation system (VHR80) and SC. An 80% *PE* reduction is achieved with the best windows (W0.8) and the best insulation options, besides a heating source such as a WBP is needed.

Package III, oriented to an improvement of the building service systems, starts with the renovation or replacement of old wood burning stoves (WS) and VHR60 to achieve a 20% *PE* reduction. To achieve the 60% target, the best energy source is needed (GSHP and SC) together with an efficient ventilation system (VHR80); in addition, base and attic floor insulation is required (AF420 and BF200). To achieve the highest renovation target of 80%, new windows (W1.6) and minimal insulation of the external wall are needed, thinner base and attic floor insulation is chosen but PV panels are taken into use.

4.6 Needs for renovation

If the essential requirement of ‘mechanical resistance and stability’ (Vabariigi Valitsus, 2015a − §11) is fulfilled, in most cases other important requirements are more or less connected with building physics, indoor climate and energy performance.

Most critical problems were connected to moisture. After a few decades, the lifetime of a roof cover made of asbestos cement boards is nearing its end (roof covering is becoming leaky), and owners want to replace it applying some original solution (roofs made of wooden shag shingles mainly). Damaged or missing wooden board or cracked inclination made of mortar on top of the foundation edge has to be repaired immediately; it also indicates that the condition of the foundation wall below may be damaged. Two main problems related to old unrenovated concrete and natural stone floors are rising moisture and the fact that these floors are cold. The quality of old concrete is sometimes poor; for example, there were rat holes through the concrete floor in one house. The surface of natural stone flooring is not very smooth; therefore it is harder to clean the floor or position furniture. Therefore these old floors need to be replaced for multiple reasons.

The survey of the studied houses showed different needs for renovation.

- Structural aspects:
  - renovation of basement (filling cracks between stones, replacing (adding) waterproofing between the basement and the external wall, reducing the humidity level in the crawl space);
  - replacing damaged floor beams and rotten logs in external walls;
  - replacing damaged wall cladding, replacing water flashings;
  - replacing or renovating old windows;
  - repairing or replacing roof cover and beams, adding a rainwater drainage system;
  - renovation of old stoves and chimneys (fire safety).
- Building physical and indoor climate aspects:
  - improving thermal resistance of the building envelope (ceiling, external walls, floor and windows);
  - adding a ventilation system with heat recovery;
  - minimising the influence of thermal bridges and tightening the areas of air leakage.
- Energy performance and building service related aspects:
  - improving thermal resistance of the building envelope;
  - increasing the efficiency of the energy source and the heating system;
  - adding a ventilation system with heat recovery.

5 DISCUSSION

5.1 Technical condition and structural damage

Although house owners are not willing to open up certain construction parts for thorough inspection (for example, the external cladding or the first floor if there are no other apertures), it is advisable to do so before major renovations. A complete survey of all construction elements may prevent unexpected additional work or costs during the renovation process. In addition, detailed background information allows the designer to choose the optimum renovation solutions.

Owners tend to undertake renovations in small steps based on available funds. Still, a comprehensive renovation plan should be prepared before any renovation (except for immediate repairs) is begun, as it helps to optimise the workflow and reduce the overall cost by preventing unnecessary construction or demolition. A few major renovation stages may be costlier than others and should be completed at once to prevent partly exposed construction over a longer period. If the budget for a proposed renovation stage exceeds the available funds, sometimes saving money is a better option than having an incomplete construction part.

Renovation of structures was usually not a major problem with the houses examined. Increasing airtightness and thermal insulation, installing mechanical ventilation, replacing out-of-date power or water installations are the most important renovation needs in the houses examined with a view to a better living environment.

Comparison of main damage found in this study with results of a similar study in Finland (Pirinen, 2006) showed that the main reasons for moisture damage are the same: most important cause of damage is rainwater leakages into structures and the second is connected with the capillary rise from the ground. In Sweden mould growth was found in cold attics and therefore drying the attic space is an important topic (Hagentoft et al., 2016). In Estonia, on the contrary, no mould growth in attics caused by too high *RH* was detected. The *RH* in cold attics in Estonian houses is probably lower than in Swedish houses because of higher temperatures in attic caused by high thermal transmittance of ceilings.

5.2 Indoor climate conditions

The rural houses in active use were compared to the targets in standards (CR 1752, 1998; EN 15251, 2006). It could be a challenge to combine today's residents' views about comfortable indoor climate and possibilities of traditional rural houses where large visible changes would be avoided. Acceptance of indoor climate conditions may be achieved by a change of indoor climate conditions and/or by a change of views of today's residents' about comfortable indoor climate. The current study showed that both have occurred. Even though as based on our measurements, the deviation from the indoor climate targets was large, the inhabitants' overall rating of the living environment was positive and the inhabitants did not report any health issues related to the house. Permanent occupation is usually the most important presumption for preserving the house. Therefore some compliance to the views of today's residents' about comfortable indoor climate may be accepted.

In the studied rural houses inhabitants accepted lower thermal comfort caused by the limited capacity of building service systems, large heat losses of the building envelope, savings on energy bills, stoves not properly heated due to fire safety aspects and adaptation to current habits. The literature gives many reasons for such behaviour. Tweed et al. (2014) showed that people have different expectations concerning thermal comfort and therefore it is inappropriate that temperature target values mentioned in the regulations are good for everyone: some prefer lower and some higher temperatures and others accept the temperatures in the target ranges. According to Han et al. (2009), in the cold winter occupants' thermal sensation responses in houses of the urban area are different from those in residences of the rural area. The mean thermal sensation vote of the rural area is higher than that of the urban area at the same operative temperature. Kotol et al. (2014) detected that house owners in Greenland tend to keep temperatures low to minimise heating costs. Yu et al. (2013) observed in their thermal adaptation study with people who live in a cold climate that chronic, long-term experience without indoor heating induces adaptations that make people feel less cold and uncomfortable during cold exposures than the people who have indoor heating. Andersen et al. (2009) found that in Denmark in addition to the outdoor temperature, the control of the heating was linked also to the presence of a wood burning stove. Also, the change in clothing insulation has a powerful adaptive effect on indoor temperature. Clothing is an important factor in achieving thermal comfort. When occupants are allowed flexibility in their dressing pattern, varying clothing is seen as an easy, economic and effective manner of adapting to the environment (Mishra et al., 2013). Braubach (2009) showed in the follow-up survey after the renovation work that the thermal insulation measures that were applied resulted in significant changes in indoor thermal comfort and the perception of cold was strongly reduced in intervention dwellings.

An energy (wood billet) consumption inquiry sheet was filled by inhabitants, but the results were inconsistent and inaccurate. The respondents could not separate the firewood consumption of different fireplaces like cooking stove, stoves for heating the living area and sauna stove. Therefore the measuring the woodpile did not work. Also counting the baskets of firewood brought for heating the main stoves was inaccurate because the length of billets was uneven and therefore the weight of wood in baskets varied considerably. Besides, during each day the full amount of billets in a basket was not used and a subjective fraction of basket made the counting even more inaccurate. Because the amount of billets used for space heating was unclear, the measured indoor temperatures were not related to energy consumption.

The current study showed that the *RH* was high in the houses that were unheated or periodically heated during winter, and it caused risk for mould growth. To avoid favourable climate conditions for mould growth, an option is to heat the house throughout the winter, controlled by a humidistat. The required indoor *RH* and temperature values can be continuously calculated based on the mould growth model on the wooden materials because of large amount of wooden surfaces in rural houses. Another option is to use conservation heating to decrease the indoor *RH*. Piironen & Vinha (2010) showed that the indoor temperature 3−5 degrees higher than the outdoor temperature eliminates mould growth risk in Finnish summer cottages. This needs a heating capacity of 5−15 W/m^2, causing energy costs of 200− 600 € during the period between September and the end of May. Based on indoor temperature measurements in unheated houses (Alev et al., 2011), the indoor temperature is about five degrees higher than the outdoor temperature and therefore no additional heating may be needed. The higher temperature is caused by an uninsulated ground floor, therefore in summer cottages the insulation of the ground floor is not recommended. Inhabitants of measured summer cottages gave feedback that if the dampers of stoves were left open during the cold period when these houses were not occupied 'there was no smell of mould' when they returned to the house. If the dampers are closed during the unoccupied period, the air change rate of the indoor air will be lower, the *RH* will be higher and the risk of mould growth will be higher. The windows and doors need to be closed during the unoccupied period to avoid the precipitation getting into rooms and to avoid the decrease of the indoor temperature to the outdoor temperature level.

Although there was no risk of mould growth in every room of the house, there is still a high risk that mould spores can easily spread from rooms with a higher *RH* where the mould growth risk is high to living rooms with a higher indoor temperature and no mould growth risk. Liu & Nazaroff (2003) and Airaksinen et al. (2004a) showed with laboratory experiments and Chao (2003) with experiments in occupied residential environments that the spreading of ambient particles including fungal (mould) spores through the cracks in different constructions is almost inevitable. Braubach (2009) analysed housing renovation in Germany and showed that the intervention may have had a positive impact on the reduction of dampness in indoor air.

The deterministic design level (90% percentile) of moisture excess during the winter period was 4–5 g/m^3 in both continuously heated and periodically heated houses. In houses unused and unheated during winter it was 1−2 g/m^3. Piironen & Vinha (2010) measured similar design level values in Finnish summer cottages. The average moisture load (used for stochastic analysis) during the winter period was 2.5–3.5 g/m^3 in continuously used houses, 1–2 g/m^3 in periodically heated houses and 0–1 g/m^3 in unused houses. Similar moisture excess values were measured in Norway (Geving et al., 2008). These values can be used in deterministic or stochastic analysis for renovation solutions for historic rural houses. Despite the periodic use of houses, the deterministic moisture load is not smaller than in continuously used houses: the moisture load in the periodically used houses during the critical moments is the same as in continuously used buildings. When using stochastic analysis, the moisture load in periodically heated houses can be assumed to be smaller because there are periods without moisture production, allowing the accumulated moisture in the structures to dry out. In the period when a house is not used, there is no active moisture production and the moisture excess should be zero (Equation 1, in Subsection 3.2). Nevertheless, values above zero were determined in unused houses during winter, caused by drying out of constructions.

Although the *RH* and temperature were separately measured in the bedroom, living room and/or kitchen in many houses, no significant differences were found between moisture loads in different rooms. In addition to the high air leakage rate of the external envelope and the internal walls this is because there were no separating doors between these rooms or the doors were open most of the time. Therefore, the air of these rooms was probably mixed. A good air exchange is reported as one of the reasons for no humidity problem in the current condition of Greenland's houses (Bjarløv et al., 2011).

After the first visit to the measured houses it was clear that most of the houses were leaky, periodically heated with a stove, without mechanical ventilation and with a low level of insulation (especially below the first floor and on external walls). These shortcomings cause high daily variability of indoor temperature and *RH*. Inhabitants feel these problems sometimes directly, but more often feel or see through secondary problems such as dusty surfaces, dryness, condensation on windows, static electricity, vertical temperature gradient, cold floors etc. Energy renovation of rural houses can increase the thermal comfort and alleviate the complaints of inhabitants besides reducing the energy demand of the house. In many cases the high air leakage rate compensated for the lack of mechanical ventilation. Inhabitants reported 'lots of fresh air' in their rural houses compared to apartments they had lived in before.

5.3 Air leakage and air infiltration

The air leakage of the building envelope of traditional rural houses is much larger than the average of detached houses in Estonia.

Based on measurements in traditional rural houses with log walls (58 measurements), the average air leakage rate was $q_{50} = 15$ m^3/(h·m^2) and the average ACH was $n_{50} = 21$ h^{-1}. A previous study (Kalamees, 2008) about the airtightness of Estonian detached houses (114 measurements) showed that the average airtightness of a building envelope is 5.2 m^3/(h·m^2). Log houses were among the leakiest building types. Therefore, in energy calculations, air leakage should be calculated with a larger airtightness value than the base values in the Government Ordinance (Majandus- ja Taristuminister, 2015): $q_{50} = 6$ m^3/(h·m^2) for new and $q_{50} = 9$ m^3/(h·m^2) for renovated houses.

Comparison of airtightness of the building envelope of renovated and unrenovated houses showed only minor differences. Contrary to expectations, air leakage rates of renovated houses were larger than of unrenovated houses. This result may have the following reasons:

- Originally, the external walls were frequently plastered from the inside, which has a significant influence on the airtightness of the building envelope (see Figure 4.18B). During renovation works the plaster was often removed for aesthetic reasons;
- Air leakage problems were unintentional and design as well as structural solutions did not concentrate directly on the reduction of air leakage. Therefore, we cannot see the influence of renovation works on the reduction of air leakage.

Chan et al. (2012) showed that in the USA a higher reduction in the air leakage of the building envelope was achieved through weatherisation assistant programmes or residential energy efficiency programmes.

In houses with natural passive stack ventilation, the discharge generally takes place through the chimneys and the compensation through the building envelope, which means that the ACH in the historic wooden buildings depends on the airtightness of the building. The analysis of the airtightness of the building envelope and air leakage of the house during normal use showed that the house use significantly influences the house both during summer and winter. The natural infiltration was three times lower in unused houses compared to permanently used houses. The average infiltration rate correlates almost linearly with the building leakage rate in most of the cases (Jokisalo, 2008). The current study revealed a much larger influence of house use on the average infiltration rate than other factors shown by Jokisalo (2008). Typically, energy simulations are made without opening external doors and windows, or windows are opened only according to temperature during summer. This may lead to differences in real and simulated air leakage rates.

5.4 Interior thermal insulation of log walls

Design depends on assessment and performance criteria. Viitanen et al. (2011) consider mould growth one of the most appropriate assessment criteria for the hygrothermal performance of building structures as it is the first to indicate that the *MC* in structures is too high, appearing before a structure is subjected to serious damage. Mould growth may be considered mainly a health risk for inhabitants and it may be also regarded a visual problem on surfaces. In the present study, no mould was accepted ($M < 1$) between an added insulation layer and the log wall. Vinha (2007) showed that M could be over 1 independently of indoor moisture loads and wall design. Under Finnish outdoor climatic conditions, *M* was between 1.7 and 3.1, calculated based on the outdoor temperature and *RH*. Inside a structure $M > 3$ is more critical because mould spores might be transported indoors, as demonstrated by Airaksinen et al. (2004b). According to mould growth classification, there are no spores if $M < 3$ (Viitanen et al., 2007).

Viitanen et al. (2015) propose a traffic-light classification to predict *M*: green means no risk of relevant mould growth, red represents an unacceptable risk level, and the yellow range indicates a possible risk and requires evaluation by the user. For surfaces not in direct contact with the air inside (such as the contact surface of the interior insulation and the log wall considered critical in this study), it is recommended that the whole range of *M*s presented in (Viitanen et al., 2015) be expanded by shifting the limits by one unit: the green light up to $M = 1$ and the yellow light up to $M = 3$. Values above 3 would be marked with the red light and considered unacceptable. A similar colour coding is used in this thesis in Figure 4.27 and Figure 4.28. It should be noted that there is a rapid transition of *M* values from 1 to 3, as shown in Figure 4.27 (only a few combinations marked with yellow); therefore, taking $M = 3$ as a criterion adds many risks but does not change the working design considerably. Accordingly, it is not advisable to design an interior insulation solution in the yellow area shown in these figures.

Based on Figure 4.27 and Figure 4.28, we can order the main parameters based on the effect on *M*, starting from the highest:

1. water vapour resistance of the vapour barrier;
2. indoor moisture load;
3. thermal transmittance of the interior insulation layer;
4. initial *MC* of logs;
5. thickness of logs, i.e. the thermal resistance of the original wall;
6. indoor temperature level.

Installing a tight vapour barrier is more realistic than guaranteeing a low Δv_i over the life cycle of a house, therefore S_d is considered more important. Logs have to dry out to a certain level anyway, and the engineer can easily choose the thermal transmittance of the insulation layer; therefore, the thermal transmittance of the insulation layer is considered more important. The effect of log thickness and indoor temperature is low; moreover, controlling indoor temperature during the design process is impossible. Therefore, it is assigned the lowest importance.

In this study a simplified set of test reference year climate data was used, including only outdoor temperature and *RH* values and excluding sun radiation, rain and wind data. Simplified outdoor data showed higher *RH* values in the wall because of the good drying potential of sun radiation and wind; the added humidity load on the facades caused by driving rain was minimal due to long eaves of traditional detached wooden houses. Simplified climate can be interpreted as a house shaded by trees or buildings nearby (minimised sun, wind and rain influence). In addition, the north orientation, which is exposed to minimal direct sunlight, has been the most critical to the hygrothermal performance of the interiorly insulated log wall. The durability of the north facade (paint and boarding), on the contrary, may be the best, while often the south or west facade is the most critical because of prevailing winds (wind driven rain) and the influence of the sun (deformations and deterioration of covering).

Heat loss through the external log wall can be reduced by about 50% if the parameter values specified as for the RC are used, i.e. the thermal resistance of the added internal insulation layer equals the thermal resistance of the present external wall. Based on the results shown in Figure 4.27C and Figure 4.27D, the thickness of an additional insulation layer of mineral wool could be even higher than 100 mm if a carefully installed tight vapour barrier with $S_d > 10$ m is used and/or the indoor moisture excess is kept below 3 g/m^3. Careful installation of the vapour barrier means that all sections of the vapour barrier are taped together with a special tape and the joints are fixed with slats, edges are sealed together with floors, ceilings and separating walls to guarantee a vapour-tight joint. The indoor moisture excess level can be decreased with an efficient continuous ventilation system. If vapour barrier and indoor moisture excess conditions are met and a calculation under specific conditions is made, the thermal resistance of an additional insulation layer can be more than double of the thermal resistance of the present log wall. Nevertheless, increasing the thermal resistance of the additional insulation also increases the risk of mould growth in the wall if any of the conditions has not been (temporarily) met. When choosing another insulation material instead of the mineral wool used in this study and if no additional hygrothermal performance calculations are made, it is recommended that the calculated thermal transmittance of the added insulation and the finishing layers should be equal to the thermal transmittance of the log wall before the addition of the insulation. Then the thermal conditions in the wall are similar to the RC in this study. Reduction of air leakages through a carefully installed air and vapour barrier required by interior insulation decreases energy losses through leaky log walls more than two times. Before insulation, a 150 mm thick log wall had a thermal transmittance of $U = 0.76$ W/(m^2·K); after the addition of an internal insulation of 50 mm (RC), it was $U = 0.38$ W/(m^2·K).

Log walls of continuously used houses have a lower *MC* than similar walls in summer cottages (unheated during winter). This study shows that for a heated house, the *MC* of logs before insulating must be lower than that for unheated houses. Therefore, for an inhabitant it is not safe to add interior insulation to an unheated house where the measured *MC* of logs is over 12% and to introduce the house into continuous use (being heated up) right after it was insulated. If interior insulation is added to an unheated house, but the use of the house remains unchanged afterwards, a higher *MC* of its log wall may be tolerated (Figure 4.28B). It is necessary to take into account the measured higher *MC* when designing an interior insulation solution. A risk may also result from an unexpectedly high (either temporary or permanent) *MC* of logs, which may be caused by water leakages through external cladding or through the wall near windows, snow melting on the wall, water system leakages near the external wall, roof leakages or moisture rising from the foundation (missing hydroinsulation strip).

A smart vapour barrier allows moisture accumulated in logs to dry out also towards the inside of the wall, lowering the mould growth risk in the wall faster. The inward drying ability is important when the initial *MC* of a log wall is higher than 14%. A smart vapour barrier or another vapour barrier with $S_d \leq 2$ m is preferable in unheated houses where indoor moisture excess is lower. During the daytime in summer, exterior surfaces are often warmed to the point where the exterior is warmer than the interior, thus creating an inward vapour drive into the interior, especially in unheated houses. A smart vapour barrier also mitigates the effect of and probable damage from water leakages through the roof or wall cladding, allowing moisture to dry out faster. In continuously heated houses where the moisture excess is high and the *MC* of logs is ≤14%, $S_d \geq 2$ m is preferred because an outward vapour drive dominates all year round.

The RC was considered suitable if $M \leq 1$ during a five-year period. The safety margin of the calculations consists in the following:

- In calculations, the critical moisture test reference year for mould growth was used. Although the *M* value showed an increasing trend over the course of five years, there is almost no possibility of five consecutive years with the same critical weather conditions.
- A design curve of moisture excess (90% fractile) was used in our deterministic analysis; accordingly, the moisture flow through the wall was above the average. In practice, the difference between weekly maximums and the average moisture excess measured is about a half of that (II). For a stochastic analysis, an average moisture excess with certain variations (Arumägi et al., 2015) should be addressed by future research.
- A north wall not exposed to any solar radiation was analysed, and temperature and *RH* were the only boundary conditions for the external climate. For orientations in other directions, the hygrothermal performance of an internally insulated log wall is better due to solar radiation. It should be taken into account that if a wall is wet, solar radiation may cause inward drying and considerable moisture flow into the interior insulation.

The study shows the importance of planning the building process. Logs with a high *MC* must have time to dry to a safe moisture level. When the measured *MC* of new kiln-dried logs is 22% (Guizzardi et al., 2015), the drying to a safe *MC* (measured value up to 14%) takes about a year in a heated (≈ 20 °C) and continuously ventilated (low humidity load) house. When the indoor conditions are not met, the *MC* of logs has to be measured until the specified value is reached. Also, insulation materials with a wet installation technology must have enough time to dry out before covering them with a vapour-tight layer. In the current study, cellulose fibre needed at least one week to dry in a heated (≈ 20 °C) and continuously ventilated (low humidity load) room to an almost stable *MC* of 8 kg/m^3. The mentioned stable *MC* of cellulose fibre cannot be reached in an unheated house or with high humidity loads, the measured *MC* of logs has to be ≤12%.

Interior thermal insulation is acceptable only at low indoor humidity loads (average moisture excess values during the cold period 2 g/m^3). Higher indoor humidity loads have to be avoided with continuous usage of a decent (silent, energy efficient, no draft etc.) balanced mechanical ventilation system with heat recovery. Climate control is also important during the construction process to dry out built-in moisture from the materials. Usually the ventilation system is not used during the construction period because of the high dust content in the air. Therefore, an alternative system (ventilation or drying) has to be used to guarantee the continuous high ACH in the rooms. When the step-by-step building process is acceptable by the inhabitants, it is good to use the house for a couple of years before adding the interior insulation layer. It is possible to add interior insulation sooner if additional wood-drying methods are used. To avoid cracking and deformations of wood the drying process cannot be too fast.

Even though several combinations have been calculated and are presented in this thesis, every particular interior insulation case should be calculated with dynamic heat air and moisture software to ensure the moisture safety of the wall. The results should be compared to the results in this thesis or referenced articles to avoid major errors.

The parameters presented in this thesis are based on the study of a one-dimensional wall, but for corner areas and thermal bridges, these solutions may not be applicable due to lower interior surface temperatures of the wall and probable leakage places near the corners. These areas have to be designed and built with special care to avoid mould growth. Additional research to determine parameters for these areas is needed. In this thesis the most critical conditions were chosen: test reference year considering outdoor climate with the highest mould growth risk in combination with a more critical simplified version of climate data; high *MC* of logs and a strict approach that excludes mould growth in each combination.

5.5 Energy performance

Targets for energy savings are usually derived from the macro-energy principles (EPBD, 2010) and do not take into account specific features of buildings officially protected as part of a designated environment, or because of their special architectural or historical merit, which usually renders them exempt from general requirements on the energy performance of buildings. Cultural heritage buildings deserve a special approach in addressing their energy performance in order not to lose their value. Nevertheless, users and owners of these buildings ask for solutions in energy savings.

Improvement of building service systems (ventilation and heating systems) is one of the largest energy saving potentials (up to 47% in the *PE* and up to 80% in the *DE*) because of the low energy efficiency of existing systems. These measures usually have a rather low influence on the appearance of the building. The changing of service systems, such as installation of new radiators, ventilation channels, repairs of interior finishing, could influence the interior of the building to a much larger extent.

As to building envelopes, the insulation of the external walls has the largest individual energy saving potential. This is partly due to the high thermal transmittance of original external walls and partly due to the relatively large area of the external walls of the whole building envelope. As old houses are quite air leaky, the improvement of their airtightness could be an effective energy saving measure and is rather invisible considering the appearance of the house. Nevertheless, from the practical building technology point or view, it is rational to combine insulation with the air-tightening of the building envelope.

As rural houses are usually not listed as architectural heritage, the change of original materials is not such a dramatic problem and it is more important that the original external appearance remains similar after energy renovations to keep the rural milieu. Due to restrictions on the changes of appearance, houses listed as heritage have reduced possibilities of energy savings, as on average it is possible to save 30% of energy with the improvement of external walls and windows.

Firstly, the indoor climate and thermal comfort were improved by installing a mechanical ventilation system following the airflow rates at a normal level of expectation for indoor climate. A balanced supply−exhaust ventilation system with the heat recovery of at least 60% is proposed to be installed as the new ventilation system. Secondly, the thermal transmittance of the envelope was decreased to avoid asymmetric radiation and draft (in energy renovation package II and combinations with higher energy improvement). Thirdly, the old heating system was renovated or replaced with devices easier to use and less time consuming (concerning the heating process) for the inhabitant by increasing the efficiency of the energy source and the heating system at the same time. The increase of thermal and living comfort should be of higher importance to the inhabitants than the initial cost of the renovation works, but it is complicated to combine the living quality with energy improvements in the calculations.

Some renovation measures can be considered cost-effective over a period longer than 20 years (Alev et al., 2015a). For example, adding additional insulation to the floor or the external wall is not economical when considering the investment cost over a period of 20 years, but when calculating over a longer period like 30 years, then it becomes economical. When the repair or replacement cost of the wooden cladding is considered as a periodic cost to preserve the visual appearance of the house and not as a part of energy renovation measures, then the additional insulation of the external wall may become cost effective.

As the prices for wood pellets are very low compared to electricity and the weighting factor for wood is also almost a third of that of electricity, it is not economical to replace WS with a GSHP or an AWHP (Alev et al., 2015a). Even the replacement with a WPB is not economical considering the investment and the higher cost of pellets compared to wood billets. The main reason for replacing WS or WPB with electric heating sources may be their less labour-intensive operation.

Taking into account that the indoor climate needs improvement anyway and therefore a high quality ventilation system with heat recovery is installed, there is no need to calculate only the energy saving from the improvement. To lower the national energy use in the residential sector, the government should provide supporting mechanisms to encourage homeowners to make their houses more energy efficient. The current cost-effective primary energy use level of the studied detached houses is around 250 kWh/(m^2·y), which is still relatively high and the target level can and should be lower (Alev et al., 2015a).

Risholt & Berker (2013) described renovation habits concerning private houses in Norway: homeowners tend to undertake mainly decorative renovation works to improve or preserve the visual appearance of the house, a smaller number of homeowners, who are often building specialists, have made energy-efficiency related renovation works. Risholt & Berker (2013) point out that lack of knowledge and bad advice from craftsmen are the main barriers that stop homeowners from undertaking energy-related renovation works. In Estonia the preferences and knowledge about renovation works seem to be similar to Norwegian practice, therefore the educational aspect appears to be the key to comfortable indoor climate and energy-efficient homes.

5.6 Comparison of Estonian results with Finnish and Swedish results

The following comparison is made based on articles II and V, which included houses from three countries. Of the measured houses 23 were one-storey houses, which is a typical old building type in Estonia, only one house had two storeys. In Finland nine of the houses had one storey and eleven had two storeys. In Sweden, all measured houses were two-storey houses.

Different foundation structures in the investigated houses are slab on ground, ventilated crawl space and non-ventilated crawl space. In Estonia the traditional foundation structure is closed crawl space. The crawl space is not ventilated and the foundation wall is sealed with a thick soil layer from the inside. In the selected houses the closed crawl space was originally the most common foundation type. The same foundation type can be found also in Swedish and Finnish houses. In Finland the most common foundation structure is ventilated crawl space.

In the winter period the indoor temperature in continuously used houses was significantly higher (2.6 °C, $p = 0.0004$) in Estonian and Finnish wooden houses than in Swedish stone houses. The reason for lower temperatures in Swedish houses is the combination of about three times higher thermal transmittance of thick stone walls (compared to wooden walls in Estonia and in Finland) and unsealed windows (in most of the Estonian and Finnish houses the windows were sealed). The sealing of windows was not related to the airtightness of the house. The average temperature in the winter period was 21.1 °C in Estonian houses, 20.6 °C in Finnish houses and 18.4 °C in Swedish houses.

In Estonia the average indoor temperature is below the targets when the outdoor temperature falls below −20 ºC and in Sweden the average indoor temperature falls below the target values when the outdoor temperature is below 0 ºC.

The correspondence of the indoor thermal conditions to the target values is similar when comparing the winter period and the whole year. During the summer period the correspondence is better: in summer indoor temperatures out of target values show twice lower occurrence than those during the winter period in the studied houses in Estonia and in Sweden. In Finland the target values are not met during 9−10% of the time all year round.

Although there were differences in temperatures, there were no significant differences in humidity levels between wooden houses in Estonia and stone houses in Sweden. However, there was a significant difference ($p < 0.05$) between the wooden houses in Finland and in Estonia: the indoor RH was about 2% lower all year round in Finnish houses compared to Estonian houses. The average RH in the winter period in Estonian houses was 35%, in Finnish houses 34% and in Swedish houses 40%. The indoor RH in the summer period was 60% both in Estonian and Swedish houses and 55% in Finnish houses.

Plastered external walls caused an about 5% higher indoor RH all year round in Estonian and Finnish houses ($p = 0.04$ in summer and $p = 0.05$ in winter). When Swedish houses were included (all plastered stone walls), then p-values were even smaller (0.02 and 0.008, respectively).

Significant ($p < 0.01$) differences in moisture load were also found between continuously used houses in Estonia and Finland or Sweden. The differences between the countries were caused by a combination of factors such as mechanical ventilation, heating system, airtightness of the external envelope, heated area and living density. The highest average moisture load in continuously used houses was in Estonia (2.5–3.5 g/m^3) and the lowest in

Finland (~2 g/m^3). Due to the small number of continuously used houses analysed and high variance of factors, no further conclusions were drawn.

In the compared stone houses with the highest thermal transmittance the additional insulation of the external wall improved the energy performance (both *DE* and *PE*) twice in Estonian and three times in Finnish houses.

In the countries compared, energy renovation measures are selected on significantly different bases when following the national regulations: to meet the targets in Finland the external appearance of a house may easily remain untouched; in Estonia only minor changes on the external side of a house are needed; but it is impossible to achieve the target values of Swedish regulations without major renovation of the externally visible part of a house. It shows the need to distinguish different levels for the energy renovation in national regulations.

The influence of the climate, the heating system and the building typology is illustrated in Figures 4 and 5 in article V. The same energy packages in different countries showed a lower influence of the climate (*DE*: 7−25%, *PE*: 6−19%) because the climate conditions in the studied locations are similar. The building typology was found to have higher influence (*DE*: 38−75%, *PE*: 7−36%). Although all the houses were old detached houses, the measures and the construction materials used were different, which means also significant variations in energy performance values. Nevertheless, the energy source had the highest influence on energy savings (*DE*: 88−114%, *PE*: 58−73%), which indicates that replacing the old ineffective heating sources with more efficient ones can give the largest saving in a cold climate zone in every detached house.

6 CONCLUSION

6.1 Technical condition

Wooden constructions have a long service life if damp conditions are avoided. Therefore, every component of the building envelope should be inspected for moisture-related damage as this is the most common type of damage.

The overall condition of load-bearing structures in the Estonian rural houses based on the examined houses is satisfactory. Still, the following replacement or improvement needs became evident:

- renovation of the foundation: typically by eliminating cracks in masonry, adding a waterproofing membrane, eliminating the possibility of a frost heave in the foundation;
- replacement of damaged logs in the external wall: typically one to three lower layers and under windows;
- replacing (or, in a few cases, repairing) the roof to ensure its watertightness;
- repairing or replacing all the water drainage system components;
- repairing or replacing the cladding on the external wall;
- improving the airtightness of the building envelope and windows.

Most of these renovations and improvements are most expediently completed together with energy renovation works. The concurrent effect will then be greater: lower total costs and better final quality.

6.2 Indoor climate

The average indoor temperature in the studied houses in the winter period was 19.4 °C. The indoor *RH* was in the range of target values except on extremely cold days. There is a high risk of mould growth in unheated or periodically heated houses due to the high indoor *RH* levels mainly during the winter period. The mould growth risk existed in 27% of the measured Estonian houses. Mould growth risk is higher on areas with high thermal transmittance; therefore the construction rather than the usage of the house plays a major role.

Almost none of the measured houses corresponded to the target values of indoor climate category III. The low correspondence of indoor climate to the target values in continuously used houses was mainly caused by the daily instability of the indoor temperature and the *RH*. The average daily *RH* variation was 6.0% during winter and 6.5% during summer in the continuously used houses.

Measurements in the studied houses in combination with the questionnaire completed by inhabitants showed that the indoor climate in all historic rural houses needs improvement to achieve correspondence to the modern criteria for general thermal comfort as the questionnaire revealed some problems with local thermal comfort (cold floors, vertical temperature difference). Our comparison of continuously used houses with unheated houses or periodically heated houses showed similar problems but their significance and time of occurrence were different. The main problems in order of importance were cold floors, unequal and unstable room temperatures, too low or too high indoor air temperatures, poor lighting, vertical temperature gradient, dust and dirty surfaces and too dry air; other reported issues were less common.

Based on the questionnaire, the main problems were related to unstable or too low (surface and indoor) temperatures. Indoor temperature could be easily regulated with the length of heating and no temperature regulation related complaints were recorded. According to the results from the questionnaire and climate measurements, it can be concluded that the inhabitants have well adapted to lower temperatures and consider the overall indoor climate as good. To obtain more stable indoor climate, the heating system should be renovated or replaced and a ventilation system with heat recovery should be installed. When only building service systems are renovated, problems like cold floors, draught or vertical temperature gradient will still remain. To eliminate these, an air and vapour barrier and thermal insulation have to be installed to external walls and ceilings and floors have to be renovated.

The average moisture load during the winter period in continuously used houses was 2.5–3.5 g/m^3 and in unused houses 0–1 g/m^3 and the corresponding higher 10% critical level during the winter period in continuously used houses was 4–5 g/m^3 and in unused houses 1–2 g/m^3. Larger houses with lower living density showed lower moisture loads. In houses not used during winter there is still an indoor humidity load due to the drying of structures.

6.3 Airtightness and air infiltration

The mean air leakage rate at the pressure difference of 50 Pa was 15 m^3/(h·m^2) (minimum 3.9 m^3/(h·m^2) and maximum 35 m^3/(h·m^2)). The mean air change rate at the pressure difference of 50 Pa in all the databases was 21 h^{-1} (minimum 5.1 h^{-1} and maximum 56 h^{-1}).

According to the results, the most significant factor affecting the airtightness of the house was the internal covering of the external walls (a layer of plaster or plywood). The typical air leakage locations in the studied houses were junctions between the ceiling or floor with the external wall, envelope surface, junctions between external walls and leakage around and through windows and doors. More attention should be paid to the tightening of the building envelope.

The average air infiltration rate in such leaky houses during normal house usage was 0.57 h^{-1}. Together with increasing the airtightness of the building envelope more attention should be paid to the performance of ventilation.

House usage influenced significantly the correlation between the air infiltration rate and the airtightness of the building envelope. Seasons influenced the infiltration less.

6.4 Interior thermal insulation of log walls

An interiorly insulated log wall was analysed by varying the indoor humidity load, average indoor temperature, the thickness of the log wall and an additional insulation layer, the initial moisture content of logs and the vapour diffusion thickness of the vapour barrier using a previously validated hygrothermal calculation model. It is important to note that the hygrothermal calculation model was validated in cold climate conditions, and therefore the results of simulations presented in this thesis apply to a wall in a cold climate.

Based on the validated hygrothermal model in software WUFI, three different interior insulation materials were analysed. The initial moisture level in the log wall, the thickness of the logs and the insulation layer, the vapour barrier and the indoor humidity load were varied in the model. The hygrothermal performance of cellulose fibre and mineral wool interior insulation systems was similar. The main difference was that cellulose fibre was installed by a wet method and the moisture had to dry out before covering it with a vapour barrier. Cellulose fibre insulation has to dry at least for one week in a heated (≈ 20 °C) and continuously ventilated (low humidity load) room after installation and before covering it with a vapour barrier. The reed mat interior insulation performed differently; it allowed the log wall to dry out also towards the interior side; in addition also the thermal conductivity of reed was lower than that of mineral wool or cellulose fibre. The airtightness of the log wall should be ensured by precise log cutting technologies and improved by sealing ribbons between the logs.

The mould growth risk was described for each combination, and based on these results, the combinations were considered as hygrothermally safe (no mould growth in the wall) or non-functioning (mould growth index over 1).

The main conditions and parameters required in order to avoid mould growth risk in an interiorly insulated wall structure are as follows:

- The water vapour resistance of a vapour barrier depends on the use of the house and its indoor humidity load; therefore, the choice of an appropriate material should be based on the values indicated in this thesis or else calculations are required in each individual case.
- The maximum thermal resistance of an additional internal insulation layer with finishing layers should not be above the thermal resistance of the log wall before the addition of the insulation. If an improved vapour barrier with efficient sealing methods is used, lower indoor moisture excess is guaranteed with ventilation, hygrothermal calculation for a specific case is made and increased risk of mould in the wall can be tolerated, then the

thermal resistance of an additional internal insulation layer can be more than double of the thermal resistance of the existing log wall.

- Before insulation, a log wall has to be as dry as possible, i.e. at the measured initial average moisture level of moisture content ≤ 12% if mineral wool with a vapour-tight barrier is used.
- It is necessary to ensure the airtightness of a wall and especially of the vapour barrier covering the interior insulation; any penetrations (electric installations etc.) are unacceptable.
- It is necessary to guarantee the required ventilation and heating in a house by means of reliable technology.

Changing the water vapour resistance of a vapour barrier or indoor moisture load was found to have the greatest effect on the mould growth index, whereas the average thickness of logs and indoor temperature levels had a small effect on it. This means that the choice of the right vapour barrier and its careful installation, together with low (controlled) indoor moisture loads, are the primary conditions to avoid mould growth in an interiorly insulated log wall.

6.5 Energy performance

The survey of the studied houses indicated that renovations relate to the diverse aspects of the structure, building physics and indoor climate, as well as energy performance and building services. For the improvement of energy performance, different renovation measures are possible. To make historic rural houses more energy efficient and to improve the indoor climate, different alternatives, such as the renovation of their thermal envelope, heating and ventilation systems, can be used. The energy performance analysis conducted in this study indicated that it is possible to meet Estonian requirements for the energy performance of buildings with a smaller or larger effect on the appearance of the house.

The analysis showed that the improvement of building service systems and the energy source has the largest energy saving potential. With a minimal influence on the appearance, this is a potential starting point to improve the energy performance and indoor climate of a building. Because national energy saving targets cannot be achieved by an improvement of building service systems alone, the improvement of the building envelope is necessary.

The building envelope of old rural houses needs improvement also due to its high thermal transmittance and air leakage. The insulation of the external wall has the largest single structural energy saving potential partly due to its high thermal transmittance and partly due to the relatively large area it comprises.

To achieve energy performance targets, three energy performance levels with three different renovation strategies (minimal influence on the appearance of the house, improvement of thermal comfort, improvement of building service systems) were proposed. The results are useful to establish energy performance requirements for historic rural houses and informative to the final stakeholders.

6.6 Recommendations for the practice

It is strongly recommended to have a complete building renovation plan composed by a professional designer and engineers. It is more efficient to combine different renovation works as then the overall result will always be cheaper and of higher quality.

Technical condition of structures:

- Clean the area surrounding the house periodically to avoid ground level rise.
- Replace damaged lower logs and logs under windows, add a waterproofing layer below the first log row during the log replacement.
- Fill the cracks between the stones in foundation masonry with lime-mortar.
- Replace the damaged wooden board covering of the foundation edge (wide wooden board is preferred over an outwards inclined mortar layer).
- Increase the air change rate in the crawl space by adding or opening closed ventilation holes through the foundation wall.
- Repair any water leaks through the roof or replace the old roof cover. Ensure the water tightness of the joint between the chimney and the roof cover.
- Repair or replace the damaged water drainage system components.
- Repaint the cladding of the external wall and replace damaged cladding.

Indoor climate and energy performance

- Install the mechanical ventilation with heat recovery to save energy and ensure sufficient indoor air change rate (ventilation airflow 0.42 $l/(s \cdot m^2)$).
- Repair or replace old stoves with new ones that provide decent heating power during cold winter and guarantee fire-safety of the house.
- Replace and insulate the cold floors with at least 200 mm insulation layer.
- Add at least 200 mm thermal insulation and sheeting above the ceiling, removal of the sand layer is not necessary.
- If a damaged cladding of the external walls needs replacement, add at least a 150 mm thick additional thermal insulation layer below the new cladding and move renovated or new windows to the insulation layer.
- If automatic heating system is preferred, install either a wood-pellet boiler, air-water heat pump or ground source heat pump depending on the budget and available land needed for a ground source heat pump.

Air leakage and air infiltration

- Do not remove continuous plaster or plywood layers from walls and ceilings during renovation if not necessary (removing these increases the air leakage rate), otherwise replace these with a correctly sealed air- and vapour barrier.
- Stove dampers should be left open during the cold period if the house is unoccupied, but windows and doors should be correctly closed.

- Include a carefully sealed vapour barrier to the inner side and a wind barrier to the outer side of the building envelope during additional insulation works.

Interior thermal insulation of log walls

- Interior thermal insulation should be considered only when exterior insulation is not possible.
- A 50 mm thick additional interior insulation layer with a decent water vapour barrier added on the old dry log wall is generally acceptable when conditions described in chapters 4.4 and 6.4 are met.

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Saaremaa Ühisgümnaasium	2006	Keskharidus
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Keel	Tase
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saksa	kesktase
vene	algtase

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15.-29.08.2016	Moisture in Materials and Structures, Taani Tehnikaülikool
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17.-18.02.2010	Solar Energy Systems, Tallinna Tehnikaülikool

Teenistuskäik

Töötamise aeg	Tööandja nimetus	Ametikoht
2013 - 2016	Tallinna Tehnikaülikool	Nooremteadur
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Language competence/skills

Language	Level
Estonian	Native
English	Fluent
German	Average
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Special courses

Period	Educational or other organisation
15–29.08.2016	Moisture in Materials and Structures, Technical University of Denmark
6–10.04.2015	Heat and Mass Transfer in Building, Kaunas University of Technology
20–28.08.2014	Net-Zero Energy Building Modelling and Design for High Performance, Summer School, Concordia University, Canada
17–18.02.2010	Solar Energy Systems, Tallinn University of Technology

Professional employment

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2013–2016	Tallinn University of Technology	Early stage researcher
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PUBLICATIONS

Articles in peer reviewed scientific journals

Alev, Ü. and Kalamees, T. (2016) ‘Evaluation of a technical survey and the renovation needs of old rural wooden houses in Estonia’, *Journal of Building Survey, Appraisal & Valuation*, 5(3), pp. 275–290.

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PAPER I

Alev, Ü. and Kalamees, T. (2016) ‘Evaluation of a technical survey and the renovation needs of old rural wooden houses in Estonia’, *Journal of Building Survey, Appraisal & Valuation*, 5(3), pp. 275–290.

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Evaluation of a technical survey and the renovation needs of old rural wooden houses in Estonia

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ABSTRACT

Wooden detached houses represent the majority of buildings in rural areas in Estonia. The design service life of these rural wooden building is nearing its end. Before starting major renovation of these houses, a comprehensive survey of the buildings is needed to determine all the visible and hidden damage of constructions. A renovation plan may be composed after the houses' technical condition has been examined completely. This paper provides a description of the issues that need to be reported in a technical survey of an old log house. The relevant survey method was tested on 50 houses in Estonia. Besides describing survey components and methods, detailed information is given about building envelope elements and possible variations. All possible damage detected is described and illustrated with drawings and photographs. Every envelope component of a house should be checked for possible damage during an inspection. There are hidden components, especially below the floor where opening the construction or using a flexible camera is needed for an inspection. Most often, rot damage was found in foundation wall and log wall joints, the main reasons for it being broken or missing rain protection or waterproofing for the edge of the foundation. Often damage was identified in crawl spaces (floor beams) and near water leaks in the roof.

Keywords: building survey, wooden detached houses, renovation need, damage

INTRODUCTION

Existing buildings are one of the largest properties of society. The detached house is the second most important building type after the apartment building. For example, in Estonia detached houses represent 40 per cent of the residential buildings in terms of floor area and 72 per cent in terms of numbers. Typical Estonian rural buildings were mainly constructed in the last century. Often these old rural log houses are still in use: as main homes or summer cottages. Figure 1 indicates that the majority of houses built before 1970 have a wooden construction.[1] Before the Second World War, log walls were the primary wall construction type, with the wooden frame construction becoming more widespread later. Now, log houses are gaining popularity because of their low embodied energy and because they are still a usable building type.

Age is commonly considered the determining factor not only in the deterioration process but also in the overall performance of a building.[2] About 71 per cent of rural houses are over 50 years old, and about 59 per cent are more than 70 years old.[3] Typical design service life is 50 years. Service life

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is the 'period of time after manufacturing or installation during which all essential properties meet or exceed minimum acceptable values, when routinely maintained'.[4] As design service life is over for most houses, it is necessary to develop a strategy to extend their service life and improve their current technical condition. Other reasons for renovation may include: giving a new function to rooms, relocating/removing internal walls to modify internal space, preserving an old style, energy efficiency,[5] indoor climate and user satisfaction,[6] etc. A correct understanding of the current technical condition and the reasons for potential damage to a house is needed to estimate the cost and time required for any major renovation works. Improving the visual appearance of the house is only a minor reason for any major renovation works. Typical solutions, then, include replacing old utility systems or energy sources with more efficient ones in a building, or improving the thermal performance of the external envelope of a house.[7]

There are different methods for conducting a building survey evaluating the physical and functional state of a building. A large number of houses can be examined with a perimeter walk around during survey using simple classification to evaluate only the building components visible from the exterior of a house.[8] EPIQR (Energy Performance Indoor Environmental Quality Retrofit) is a methodology developed to assist apartment building owners who are considering the refurbishment or retrofitting (upgrading) of their building stock.[9] Although a short walk-through building audit is a fast and good method for a first opinion, it lacks any information about the condition of many hidden construction elements, which can be investigated only by being inside the house. Hoxley[10] provides a technical framework for the general procedures of building surveying. One modern method to detect some of the hidden problems of a house without opening up its structure is infrared thermography,[11] allowing the detection of structural defects, moisture accumulation and ingress in addition to traditional energy-specific defects. Pirinen[12] presents a building survey method to determine any possible health hazard. Annila et al.[13] specify methods usable for the detection of moisture and mould damage to building stock. Hometalkoot[14] presents various technical problems for a different house typology in Finland. A different approach is set out by Che-Ani et al.,[15] who have developed a priority ranking system for professionals. Regardless of the comprehensive evaluation, which uses numerical coding in survey form, a self-explanatory result effectively reflecting the condition of the house (dilapidated, fair or good) is provided. When a look at a construction part does not reveal any damage to the owner of a house, usually destructive testing methods for evaluating the construction condition of covered elements are not allowed. This means that often hidden load-bearing constructions are eventually evaluated using indirect methods.

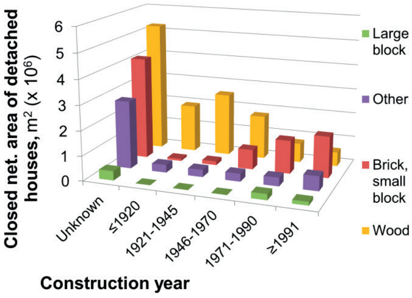

Figure 1: Floor area of detached houses in Estonia as broken down by load-bearing structure material and construction year.

Before major renovations are planned to address energy-related deficiencies (thermal bridges, high thermal transmittance of the envelope, poor ventilation, etc.),[16] it is advisable to conduct a comprehensive technical survey of a house. Once there is a complete overview of its technical condition, it is possible to combine repairing constructional damage and energy-related renovations. By combining these, owners can lower building costs compared to when these works are done separately; also, any renovations will disrupt the normal life of the inhabitants only once.

By describing building survey methods and locations, this study provides an overview of construction parts of the external envelopes of old detached houses of logs built before the Second World War. Main damage to external constructions are pointed out after describing them. This study focuses on offering guidance on where to locate damage that will later help to provide specific solutions to fix it.

HOUSES EXAMINED

The following technical survey was tested on 50 houses mainly built before the Second World War in Estonia. The average construction year for these houses is 1903 (1810…1950), and the average net area of the living space in them is 80 m^2 (34…180 m^2). Half of the houses examined are in everyday use all year around, one-quarter are summer cottages (unused and unheated during winter) and one-quarter were used periodically also during the cold season. The two main timber species used for building log walls and other wooden construction parts are Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris L.*).

The houses are mainly heated using wood-fired ovens. Typically, there is only passive stack ventilation and window airing. Domestic hot water was heated on kitchen ranges originally and mostly by electricity nowadays.

The survey included an inspection of the house, a questionnaire with owner and laboratory analyses of wood section samples taken with an increment borer. The inspection focused on load-bearing and building envelope structures such as walls, floors, roofs, foundations, windows and doors. This means that building service systems are not addressed in this study. Clear tape was used to take samples of possible mould growth on internal surfaces for laboratory analyses to confirm a mould finding and specify the species found. The moisture content of wooden elements was analysed with an electronic wood moisture meter (Gann Hygrotest LG 3) with a drive-in electrode (M 20). Damage and important structural components were photographed.

Guidance is provided for professionals on conducting a comprehensive survey of rural houses based on this example in Estonia. First, information required for a complete survey report is listed. Secondly, a short construction description and main materials used in the houses examined are given. The information included in a report should be like that in this paper, except that this paper provides multiple different versions of construction types. Thirdly, damage found in the houses examined is described, including the probable causes. A building survey report should provide similar information about any damage identified in the given house. Relevant photographs taken during the survey should be included in the final report to illustrate the problems identified.

RESULTS

Foundation

Survey

Important issues to examine during a building survey include:

- Soil type and properties.
- Technical condition: cracks, connection of masonry.
- Depth and thickness of the foundation wall.
- Material of the foundation wall.
- Waterproofing and drainage.

- Inclination of the ground around the house.

Foundation wall depth in the ground and its condition can be checked by digging locally near the wall with a spade (pit up to 50 cm wide). Overall foundation dimensions should be recorded: depth in the ground, height above the ground and thickness. Attention should be paid to the mortar in between the masonry: how much has fallen out or crumbled. The mortar layer should be continuous without any cracks. Any cracks found need to be recorded and repaired as soon as possible. An estimate should be given of how much of cracks between stones needs to be refilled with new mortar. The entire foundation wall should be checked for cracks, their placement marked on a sketch and the cause of cracking given: an uneven rise or movement of the foundation wall, frost damage or unsuitable materials. If the foundation has already been rebuilt with concrete, the quality of the concrete and the number of cracks and their placement should be reported in the survey. The rainfall protection system should be described if the foundation wall projects from the wall surface. If the foundation edge is covered with wooden board to direct rain away, then its condition and fastening should be described. An estimate of the lifetime left for the wooden board before its replacement should be given. If the foundation edge is covered with mortar, it should be checked if it has disintegrated off the foundation (cracking below the mortar layer and between the mortar and the first log).

Technical solutions, conditions and renovation needs: Foundation

Nearly half the foundations were built of limestone, with the rest built of granite. Only a few houses had foundations rebuilt with concrete. A couple of dry-laid stone foundations were identified. Usually, the foundation depth in the ground was no more than 50 cm; often it was less. The foundation width ranged from 30 to 60 cm. The height of the section of the foundation above the ground (foundation wall) ranged from 0 to 60 cm. In half the houses, the foundation wall height was below 20 cm. The houses examined have projecting or receding basement walls. One-quarter of the houses had an additional mortar layer above the foundation. Foundation designs are shown in Figure 2.

Low foundation depth in the ground can cause undesirable rising and movement of structures due to freezing. If the foundation depth in the ground is less than that of the frozen ground in winter, yearly frost boils may damage the foundation. Foundation stones may come apart after water penetrating the foundation structure freezes. Also, natural stones may decay due to physical or chemical weathering. There may be cracking due to the different expansion of stones when granite and limestone are used in conjunction.

If the condition of the first log row is good, appropriate wooden board above the foundation edge inclining outwards helps to keep the foundation and log wall dry. The inclined covering plane may be made of mortar also when direct contact between logs and mortar is avoided. Mortar covering tends to crack and fall off the foundation edge, leaving the foundation exposed to rainwater. If wooden board is placed correctly above the foundation edge, rainwater will not penetrate the foundation, and any moisture rising from the ground can easily dry out.

Foundations covered with wide wooden board and with lime-mortar filled joints between stones are in the best condition. Wooden board protects the foundation wall from rainwater. There are fewer problems with the foundation on the same plane with the wall or even inside the wall plane. Damaged or missing wooden board or cracked inclination made of mortar on top

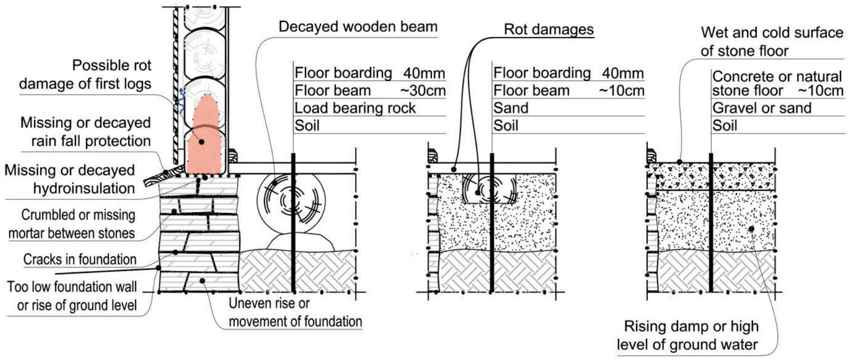

Figure 2: Section of a foundation, base floor and external wall. Main construction elements and common damage.

Figure 3: Uneven settlement of the foundation and an excessively low foundation wall (left) and cracks in the foundation due to the soil freezing and damaged water boarding (right).

of the foundation edge has to be repaired immediately; it also indicates that the condition of the foundation wall below should be checked for damage.

Base floor

Survey

Important issues to examine during a building survey include:

- Soil type and properties below the floor.
- Technical condition of beams and floorboards: rotten depth and beam-ends, fixing of boards.
- Support of floor beams, uneven settlement.
- Moisture content and cracks in concrete or the natural stone floor.
- Air exchange in the crawl space or basement, airing opening through the foundation wall.
- Material and technical condition of insulation material below the floor (if any).
- Condition of the floor finishing layer (paint, varnish, tiles etc.).

A survey of base floor should start with determining the floor type: is it floor with a crawl space or a slab on the ground, insulated or not? If there are no openings through the floor, then a small hole can be drilled through the floor, and through the hole a portable flexible inspection camera with a light can be used to explore and take photographs. Fungal and insect damage to the floor beams and the underside of the floor boarding should be assessed. Special attention should be paid to the ends and support of the floor beams. Also, the causes for any uneven settlement of the floor will probably be clear after an inspection of the crawl space. The condition of the ventilation holes through the foundation wall may be checked from both the crawl space and outside.

In case of a slab on the ground, a small hole can be drilled through the floorboards, or parts of the boards should be removed to get a complete picture about the condition of the floor. If the floor is made of concrete or natural stones, it should be checked for cracks showing an uneven rising of the floor. Moisture content should be measured and evaluated, because high moisture content indicates rising capillary damp. From the rooms, the quality and renewal need of floor finishing should be recorded, including the number of any loose tiles.

Technical solutions, conditions and renovation needs: Base floor

Selection of base floor designs and common damage are shown in Figure 2. Most floors with crawl space are supported by roundwood beams and wooden boards. Floor beams can be laid on big stones (Figure 4) directly on sand (Figure 5). Wet rooms usually have concrete floors covered with ceramic tiles without a dedicated waterproofing layer.

In many of the houses examined, wooden beams had rot damage. Therefore, the effective cross-section of the beams had decreased and the floors had sagged. Hygrothermal conditions in the crawl space were almost always favourable for mould growth or even rot. These favourable conditions may be due to one or more causes:

- Very low air exchange in the crawl space indicating absent, closed or too few ventilation holes through the foundation wall.
- Temporary free water in the crawl space indicating an excessively high level of groundwater or freshet (rain or melted snow) entering the crawl space.
- Wooden beams in contact with wet soil indicating that the inclination around the house does not guarantee water flowing away from the house or that there is

Figure 4: Wooden floor on roundwood beams (left) damaged by rot and insects (right).

Figure 5: Floor beams inside damp soil (sand) (left). Floor planks are ~4 cm thick, and a ~1 cm thick layer from the lower surface is rotten (right).

no soil layer (20 to 25 cm of gravel or crushed stone) to effectively reduce capillary rise.
- Insufficient drainage system.

Adding insulation below the floor definitely raises the surface temperature of the floor, but the temperature in airspace between insulated floor and soil will decrease causing an increase of RH. Often drying out moisture and reducing the radon concentrations in the crawl space are not addressed. The study[17] showed that the joint between the floor and the external wall is very leaky; thus, almost no attention has been paid to the airtightness of the floor constructions.

The study identified both old uninsulated concrete floors cast directly on sand and floors made of natural limestone slabs in a few houses. Two main problems related to old unrenovated concrete and natural stone floors are rising damp and the fact that these floors are cold. The quality of old concrete is sometimes poor; for example, there were rat holes through the concrete floor in one house. The surface of natural stone flooring is not very smooth; therefore it is harder to clean or position furniture.

External walls

Survey

Important issues to examine during a building survey include:

- Technical condition of the first log rows: rot damage, widened cracks between logs.
- Condition of the corner notches of the log wall.
- Material and condition of the waterproofing layer between the foundation and the wall.
- Technical condition of wall cladding: finishing, fixing and rot damage.
- Joints of windows and doors to the log wall.
- Condition and installation quality of window sills.
- Material and installation quality of insulation systems (if any): insulation layer, wind barrier layer and additional air gap before the cladding.
- Solution for making the log wall airtight: material used between logs and covering solution.
- Condition of rainwater downpipes.

A log wall may be mainly inspected from outside because higher water loads are from outside. The condition of the boarding may be evaluated, and main areas of decayed boarding should be reported. Lifetime left for wooden cladding before replacement or renovation (painting) should be estimated. Below the most decayed boarding areas, also damaged logs may be expected; hence, a few boards should be removed from these areas to get a better idea of the log wall itself. If the cladding needs complete replacement immediately, it should be removed to expose the log wall. An exposed log wall may be inspected completely for damaged logs, and any logs requiring repairs or replacement should be reported. After removing the cladding, corner notches can be checked for movements. If a notch has moved from its original location, the cause should be identified and reported. The existence and condition of any waterproofing layer below the first log row should be checked; an extensively decayed first log row may indicate the absence of a waterproofing layer.

Samples may be taken with an increment borer from the first logs and the logs below windows to ascertain the rotten depth, and rot samples may be analysed in a laboratory. For laboratory analysis, samples should have clear coding also indicated in the survey report. Samples from other wall parts may be also taken if damage is suspected. If major renovation with internal finishing replacement is planned, the old finishing layer should be (partly) removed for a complete overview of the condition of the log wall.

The condition and quality of logs below windows and doors should be reported to provide recommendations for improvement. The fixing and condition of rainwater downpipes should be checked to avoid any major water damage. A sketch should be made in the survey report of the wet areas of the log wall if detected, and the cause for the high moisture content should be ascertained. If the wet surface is attributable to trees or plants near the wall, branches or entire trees to be cut should be reported and linked to wet or damaged wall areas. Also, links between roof damage and wet wall areas should be recorded.

Technical solutions, conditions and renovation needs: External walls

Two external wall designs with main damage are shown in Figure 6. Walls of old dwellings are built of horizontal round or hewn wooden logs. The diameter of roundwood logs ranges 15 to 25 cm. Horizontal joints between logs were originally sealed with tow or moss. Wooden elements are sensitive to high moisture content. Because of low foundation walls and water coming from the ground, the lowest rows of log walls are often damaged by wood decay and wood-rotting fungi. The lowest rows of logs have been often replaced with new logs or stone walls because of that.

In about one-quarter of the houses studied, the log walls have no additional layer; half had cladding on the external side of external walls. About one-quarter of the houses are renovated and include wind barrier and insulation layers in addition to the external cladding. A couple of the houses have plastered external walls or

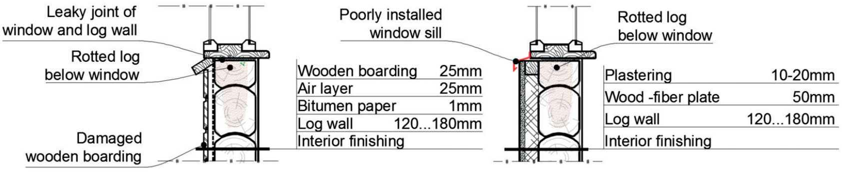

Figure 6: Typical external wall with wooden boarding (left) and plastering (right).

additional silicate masonry for rain protection. To protect the log walls from the rain, horizontal or vertical wooden boarding fixed on battens or directly on the log in a few houses is used. Vertical battens between the boarding and the log walls or wind barrier (in case of an externally insulated wall) are considered the best solution because the natural air movement in the air gap between boarding and the wall helps to dry out the wall.

A special wind barrier is not used in the external walls. Based on airtightness measurements,[18] internal plaster or tightly installed plywood boards decrease air leak. In more than a half of the houses, the log wall is unfinished from inside. In a few houses, the lower part of the wall is covered with vertical boarding (to a height of ~70 cm), which often hides the masonry wall (replacing damaged lower logs) made of expanded clay, lightweight concrete blocks or silicate stones. In a few houses, damaged logs have been replaced appropriately with new ones.

Damage to external walls

Most problems are caused by excessively high moisture loads or poor construction quality. Critical areas and causes of damage in external walls include:

- Excessively low foundation walls causing severe rainwater loads on the external surface and damage to the first log rows.
- Uneven settlement of the foundation causing cracks in the wall.
- Missing waterproofing layer between the foundation and the first log row causing high moisture levels in the first log rows and rot damage.
- Excessively short eaves causing rainwater to reach the façade.
- No or damaged rainwater piping causing local water damage to the wall or façade.
- Defective or incomplete window sills or other rainwater management systems causing rot below the window or near other wall parts affected by flowing water.

A waterproofing layer between the foundation and the wall is damaged or is not laid at all during construction. Mainly for this reason, in half the houses moisture damage is evident in the first log rows. On top of the foundation edge, mortar surface tilting outwards has been built in many houses to direct rainwater away from the wall (Figure 7, right). If any water gets between the log wall and the additional concrete edge, the drying of the log surface will take much longer and the moisture will increase the

Figure 7: The bitumen paper behind the external boarding that should stop the rain load on the log is broken and has clogged the air layer behind the boarding (right). Missing waterproofing between the foundation and the log and the mortar above the log result in rot damage to the lower log (right).

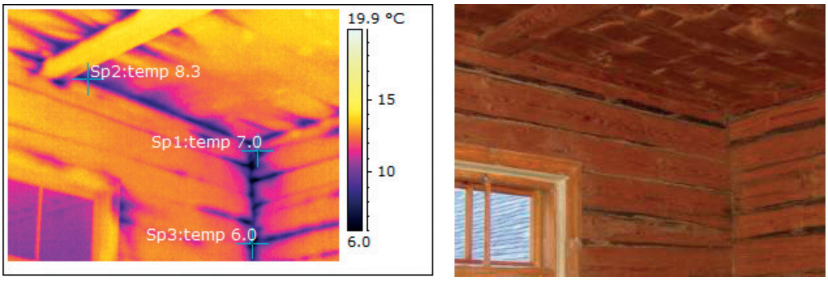

Figure 8: Old rural log houses are leaky. Air leak areas are readily visualised by a thermal imaging camera.

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risk of moisture damage to the first log rows.

The surrounding ground level has often risen due to the increased humus layer near the house, ground planning works, road construction etc. causing the foundation wall end below the ground level and log wall make contact with the soil in a few cases. Rising ground levels are often caused by poor cleaning in the area surrounding the house. Log rows in contact with the soil decay quickly and induce additional settlement in the wall, widening wall cracks and unexpected settlement in windows and doors.

In many houses, the cause for damage is not clear as there might be multiple causes for specific damage. Rainwater may splash off the soil or the foundation edge onto the first logs row of the wall. Damage is visually detectable based on rotten log surfaces. Moisture levels in logs may be measured: first, the lower part of the first log should be measured as usually there is a longitudinal crack in its middle keeping capillary moisture flow from travelling any higher. Damage may be expected if the measured moisture content of a log is >18–20 per cent or if moisture content is above 20 per cent during a long period, then logs will be definitely damaged.

Often there is damage around the windows (to a lesser or greater extent, half the houses have this problem). Most often, the log directly below the window is rotten, damaged by a missing or damaged subsill as water falls from the window directly on this log.

If rainwater periodically reaches the log wall surface, damage may be expected in any part of the wall. Water falling on the wall surface may be due to driving rain or damaged eaves. In the shade of trees or plants too close to the wall, the drying of logs slows down and there is a higher risk of damage. If the cause for damages is not addressed, the speed of decay will increase.

Attic floors and attics

Survey

In ceilings, attic floors and attics, important issues to examine during a building survey include:

- Technical condition of beams and ceiling boarding: rotten depth and beam ends.
- Sagging of ceiling beams.
- Airtightness of the ceiling.
- Air exchange in the attic space.
- Thermal insulation of the ceiling.

A survey of the attic floor should begin from inside reporting the condition of the ceiling boarding or other finishing material, including the renewal need of paint and any potential fixing errors. Structurally, the sagging of the ceiling is easier to detect from inside and then its causes may be inspected from the top. Above the ceiling, the construction, condition and sealing method of openings to the attic space should be reported.

From the attic space, first the material, thickness and condition of the wind barrier layer and insulation may be seen. Insulation quality and any potential condensation-related problems near ventilation pipes should be inspected if there are ventilation system components in the attic space. The technical condition of wooden beams used as load-bearing elements should be checked for rotting and insect damage. Also, the fixing of beam ends should be inspected, and if any sagging is evident from inside the room, its causes should be investigated.

Technical solutions, conditions and renovation needs: Ceiling and attics

Traditional ceiling designs are shown in Figure 9. The load-bearing structure of the ceiling of the top floor is made of hewn wooden beams. The large attic space between the roof and ceiling is often used for storing things that are not needed. The boarding (often top rough boarding) is fixed on the wider edges (or added slats) of the bottom of the beams. Sometimes, a second finishing layer is added below the rough upper boarding made of painted matchboards, painted plaster or a painted plywood layer. The average thickness of the insulation layer on upper boarding is 20 cm. The original insulation mixture (sand, sawdust, flax shives or hay dust mixed with clay or lime) used below the hay stack has lower thermal resistance than modern insulation materials; nevertheless, this solid mixture provides reasonable airtightness for the ceiling construction. When the houses were built, the attic was often used to store hay for animals. Hay also acted as insulation in winter; however, when animals were not raised on the farm anymore, old hay is removed from the attic (for an example, see Figure 10, left). Hence, the thermal resistance of the ceiling is lower than it used to be, and additional insulation is needed.

In most renovated houses, old ceiling boarding has been cleared of old paint or replaced with new boarding. Additional thermal insulation of mineral wool or expanded clay aggregate has been added to the original insulation layer, or the original layer has been replaced. Only in a couple of renovated houses, correctly installed wind barriers above and air/vapour barriers below insulation are used. If the attic level has been renovated as a living space, the ceiling/roof is insulated with a 100–150 mm mineral wool layer between the rafters and finished with painted/papered gypsum board or a thin matchboard layer.

A leaky ceiling increases heating costs. In buildings where old solid ceiling insulation mixture has been replaced with

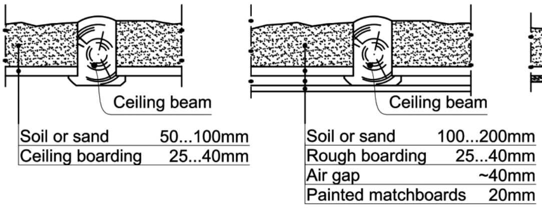

Figure 9: Typical attic floors.

Figure 10: Fire risk in the attic (left). Rot damage to wooden ceiling details insulated with soil.

only mineral wool, sawdust, hay or other unknown dust, airtightness is low. When the original insulation solutions are compared, the best airtightness is achieved with a clay and flax shives mixture. Renovated rustic-style ceilings made of two-layer overlapping unedged wooden boards had the lowest airtightness. Ceilings covered with continuous plaster layers or plywood had better airtightness. Often during renovation old plaster or plywood layers are removed and the boarding behind it is cleaned and varnished, whereupon the airtightness of the house declines considerably. In a couple of buildings, the joint of between the ceiling and the chimney is leaky, causing heat loss through cracks and also fire safety issues.

If the ceiling is insulated with soil or sand and if there are water leaks through the roof, insulation may be wet permanently (or for extended periods). Wet insulation causes wooden ceiling details to rot (Figure 10, right). Insulation particles (sawdust, sand or mixtures thereof) fall into rooms through cracks in the ceiling boarding, and cleaning this dust causes extra work and inconvenience for inhabitants. The falling dust problem is solved with a double ceiling below the original one, made of matchboards or plywood. In a few renovated buildings, the old insulation has been replaced and/or air/vapour barrier has been added below the insulation layer.

Roof

Survey

Important issues to examine during a building survey include:

- Roof material and construction quality.
- Length of eaves and the roof airing system.
- Load-bearing construction of the roof: rot damage, sagging of elements.
- Technical condition: damage to roof material, water leaks.
- Technical condition of roof parts: eaves, valley, ridge, hips, gable ends.
- Roof joints with chimneys or other through elements, water leaks near flashings.
- Rainwater drainage system: gutters, downpipes and joints.

The section of a survey report on the roof should begin with the covering material, overall condition and expected lifetime before replacement of the roof. An overall opinion on the roof maintenance should be provided. If there is moss or leaves on the roof, the immediate need for clearing them away should be reported to the owners. From the attic space, all load-bearing elements, including rafters and collar beams, should be checked for movements and damage. If the ridge is not straight when viewed from outside, possible movements or sagging in load-bearing elements may be expected and should be checked from the attic.

Every possible water leak area in the roof covering visible either from inside or outside should be marked on a roof sketch, and temporary fixings (Figure 11, right) should be also recorded. Immediate repairs of leaks should be recommended to the owners. Likely leak areas are near chimneys (Figure 11, left) or other through elements, and these areas should be inspected carefully. Fixing, water tightness and any potential need for repairs in case of flashings should be indicated in the survey report. If a rainwater drainage system has been installed, every component in it should be checked for damage. Gutters need to be cleared of leaves and downpipes fixed firmly to the wall. The drainage system must be continuous, without any gaps.

Technical solutions, conditions and renovation needs: Roof

Rural houses have traditional half-hipped or gablet roofs. The roof angle is usually 45° ±10°. Roofs were covered originally with thatch or wooden shag shingles (Figure 11, left). Later, most wooden shag shingle roofs were covered with asbestos cement boards (with the old roof covering usually left underneath) (Figure 11). Thatch roofs are mainly replaced if needed, and in only one case it has been also covered with asbestos cement boards. The thickness of the thatch layer is usually 30 cm. In a few renovated houses, the roof has been covered with steel plates or asphalt shingles.

Rafters are made of roundwood 10–15 cm in diameter. Hewn battens or sawn planks 30–40 mm thick with ~30 cm intervals are used as sarking. Rafters are seated on the uppermost log or wall plate log (if any masonry wall used) using birdsmouth joints. Collar beams are also made of roundwood joined to the pair of rafters using a couple of hardwood pins. If the house is wider than 6 m, purlin plates are used in addition to collar beams between the pair of rafters.

In renovated houses, the attic space is put to use as a living space, and thus the roof has insulation between the rafters. Old hewn rafters are replaced with new sawn rafters measuring 50 x 150–200 mm.

The main function of the roof is to protect the house from precipitation. Water leaks in roof covering are the main cause for roof construction damage. Main causes for water leaks include:

Figure 11: Typical leaks: around the chimney (left) and due to excessively old roof covering (right).

- Ageing roof covering.
- Poor roof maintenance (moss and leaves on the roof).
- Faulty fastening of roof covering.
- Temporary repairs of leak areas.
- Extensive settlement of load-bearing construction.
- Defective edges or covering components.
- Holes or cracks near components passing through the roof (chimneys, ventilation pipes, antennas etc.).

Small leak areas may cause significant wet damage. Although the water amount leaking through a small leak area is small during each instance of rainfall, it provides favourable conditions for the growth of rot or mould. It is possible that not all small leaks are visible inside.

Actual water leak through the roof was found in only one house not used for years where renovation had just started. In all the other houses, the roofs have been either periodically repaired or replaced when needed. A temporary but nevertheless necessary repairing solution is shown in Figure 11 (right). Often old roofs made of wooden shag shingles (or thatch) are covered with new asbestos cement boards to prevent leaks through the ageing, old roofs (example in Figure 11, left). Laying asbestos cement boards over old roofs is faster and cheaper than replacing old roofs using the original solution. Now, after a few decades, the lifetime of asbestos cement boards is nearing its end, and owners want to replace them with the original solution (roofs made of wooden shag shingles mainly). Also, the visual architectural look of a house plays a role when its new owners want to remove the old cheap covering and renovate the house into stylish old-looking barn dwelling.

About one-fifth of the houses have problems related to the joint between the chimney and the roof. In most houses, the penetration through the roof is on the ridge, which simplifies waterproofing solutions, as there is no need to shunt water around the chimney. In two houses, the chimney has been erected at an angle to have chimney penetration through the roof on the ridge when the base of the chimney is not on the centre line of the building. Nevertheless, there are moisture damaged wooden roof components near the chimney because a few chimneys do not have the correct flashings above the roofline.

DISCUSSION

Although owners do not like to open up certain construction parts for thorough inspection (for example, the external cladding or the first floor if there are no other openings/apertures), it is advisable to do so before major renovations. A complete survey of all construction elements may prevent unexpected additional work or cost during the renovation process. In addition, detailed background information allows the designer to choose the optimum renovation solutions.

It is advisable to discuss renovation plans with the owners of a building before it is surveyed, as it helps to choose the building sections that are more important in the evaluation process. Also, major complaints from owners can help to identify the main damage or causes for damage to the structure. Accordingly, the engineer conducting the building survey should be also good at communicating with the inhabitants of the building.

Owners tend to undertake renovations in small steps based on available funds. Still, a comprehensive renovation plan should be prepared before any renovation (except for immediate repairs) is begun, as it helps to optimise the workflow and reduce overall cost by preventing unnecessary construction or demolition. A few major renovation stages may be costlier than others and should be completed at once to prevent partly exposed construction over a longer period. If the budget for a proposed renovation stage exceeds the available funds, sometimes saving money is a better option than having an incomplete construction part.

Renovation of structures is usually not a major problem with the houses examined. Increasing airtightness and thermal insulation, installing mechanical ventilation, replacing ageing power or water installations are the most important renovation needs in the houses examined with a view to a better living environment. During a complete building survey, a report should include the condition and safety of building service systems: sewage system, water system, electrical wiring, and heating and ventilation systems.

CONCLUSIONS

Wooden constructions have a long service life if damp conditions are avoided. Accordingly, every envelope component should be inspected for moisture-related damage, as this is the most common type of damage. All damage and deficiencies identified in construction elements should be included in a survey report. It is good to add a sketch about the location of damage over a larger area. The moisture content should be measured in the first log rows of walls and wooden elements of base floors. It is advisable to partly expose hidden construction elements or use a special flexible camera for inspection. Immediate repair needs such as water leaks in a roof and broken drainage components must be included in a survey report and reported to the owners. In addition to load-bearing elements, also the condition, repair needs and expected lifetime of covering components are needed, because often the covering layer protects the load-bearing structure from moisture.

The overall condition of load-bearing structures in the houses examined is satisfactory. Building structures needing replacement or improvement include:

- Renovation of the foundation: typically by eliminating cracks in masonry, adding a waterproofing membrane, eliminating the possibility of a frost heave in the foundation.
- Replacement of damaged logs in the external wall: typically 1 to 3 lower layers, below windows.
- Replacing (or, in a few cases, repairing) the roof to ensure its watertightness.
- Repairing or replacing all the water drainage system components.
- Repairing or replacing the cladding on the external wall.
- Improving the airtightness of the building envelope and windows.

Most of these renovations and improvements are most expediently completed together with energy renovation works. The concurrent effect will then be greater: lower total cost and better final quality.

ACKNOWLEDGEMENT

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PAPER II

Alev, Ü., Kalamees, T., Eskola, L., Arumägi, E., Jokisalo, J., Donarelli, A., Siren, K. and Broström, T. (2016) ‘Indoor hygrothermal condition and user satisfaction in naturally ventilated historic houses in temperate humid continental climate around the Baltic Sea’, *Architectural Science Review*, 59(1), pp. 53–67. doi: 10.1080/00038628.2015.1038980.

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Indoor hygrothermal condition and user satisfaction in naturally ventilated historic houses in temperate humid continental climate around the Baltic Sea

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Indoor climate and user satisfaction were analysed by field measurement and a questionnaire in 67 traditional rural houses in Estonia, Finland and Sweden. Our findings showed that the indoor climate in all the investigated historic rural houses needs improvement. The room temperature was mainly too low during winter. Leaky houses had also a larger vertical temperature difference. The relative humidity in the unheated and periodically heated houses was high during winter and caused risk for mould growth in 17% of all houses and 33% of unheated houses. Significant differences of indoor humidity loads in different houses were revealed depending on the living density and usage profile. During the winter period, the design value of moisture excess was 4–5 g/m^3 and the average moisture load was 2–3.5 g/m^3. The indoor humidity load in historic houses was similar to that in modern houses. The results of the questionnaire showed that main problems were related to unstable or too low temperatures. At the same time, inhabitants rated the overall indoor climate as healthy and no statistically important relations were found between average indoor temperature and complaints about too cold or too warm indoor temperatures.

Keywords: indoor climate; traditional vernacular architecture; user satisfaction; mould growth; rural houses; moisture load

1. Introduction

In the course of time, the use of historic and traditional rural houses has changed. Today people have different requirements for thermal comfort, function and energy performance of private houses. Therefore, the owners of old traditional houses have an ambition to renovate their homes according to these requirements.

The room temperature is one of the six main parameters in the human's general thermal comfort model (Fanger 1970; ISO 7730; ASHRAE Standard 55P 2003). To design comfortable houses, in addition to building characteristics such as design, construction, adaptable elements, controls and management in relation to the local climate, culture and economy (Roaf et al. 2010), the inhabitants should be given an opportunity to control the indoor temperature.

The indoor thermal conditions in historic and traditional houses have been investigated in several studies. Hunt and Gidman (1982) measured the domestic dwelling temperature and interviewed inhabitants to obtain information on thermal comfort conditions and heating patterns during winter in 1000 homes nationwide in the UK. The average dwelling temperature was 15.8°C, and homes with central heating had 3°C higher indoor temperature than those without. Nicol and Roaf (1996) surveyed the thermal comfort during summer and winter in five climatic regions of Pakistan to help the Pakistan Government to replace existing inappropriate indoor temperature standards. Indoor temperatures varied substantially in different climate and seasonal conditions. Singh, Mahapatra, and Atreya (2010) surveyed 150 vernacular dwellings in north-east India by field measurements and user rating on thermal sensation of 300 occupants. None of the houses were comfortable in winter but are fairly comfortable in pre-summer, summer and pre-winter periods. Cantin et al. (2010) investigated various thermal characteristics of historical dwellings and their differences with modern architecture in France during one-year field measurements in 11 dwellings. A stronger thermal correlation than in the modern dwelling has been underlined between the outdoor and the indoor environment. Rijal, Yoshida, and Umemiya (2010) surveyed the thermal environment and thermal sensations in summer and winter in Nepal. Since residents adjust well to the thermal conditions, they were highly satisfied with the thermal condition of their traditional houses. Dili, Naseer, and Varghese (2010) investigated thermal conditions in Kerala traditional residential buildings and

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found that natural and passive control system of Kerala traditional architecture provides comfortable indoor environment irrespective of the outdoor climatic conditions. The passive control system included insulated envelope in addition to controlled and continuous airflow inside building. Rijal et al. (2013) investigated comfort temperatures and related window opening behaviours in 30 Japanese homes.

In the assessment of indoor climate, in addition to temperature, indoor humidity is an important parameter. Too low indoor relative humidity (RH) can cause numerous health symptoms, such as dryness, primarily of the eyes, as well as of the nasal cavity, mucous membrane and skin. Sterling, Arundel, and Sterling (1985) suggested that the optimum conditions to minimize the risks to human health would occur in the narrow range of RH, between 40% and 60% at normal room temperatures. Other studies suggest somewhat lower RH values due to material emissions, odours, Perceived Air Quality (PAQ) and mould growth. Fanger (1971) concluded that the RH should not be below 20%, because dry air often produces complaints of dry mucous membranes and consequent irritation. Wyon et al. (2002) showed that 5-hour exposures to low humidity conditions at +22°C (RH 15% and RH 5%) have a negative effect on the tear film quality that does not occur above the level of RH 25%. Sunwoo et al. (2006) found that to avoid dryness of the eyes and skin, it is necessary to maintain RH greater than 30%, and that to avoid dryness of the nasal mucous membrane, it is necessary to maintain RH greater than 10%. Another limitation for the low RH is the control of static electricity. RH above 40% or 55% when under floor heating is used will prevent most shocks (Brundrett 1977). Paasi et al. (2001) studied the surface resistivity and charge decay times for several materials as a function of relative humidity in the range of RH 5–70%. The results show that special care is needed in the electrostatic discharge management if RH below 20–30% is anticipated. However, humidification is not common in Baltic and Nordic countries, it is a matter of discussion if the envelopes should be designed for humidification, as sensitive people use humidifiers. If humidification is decided to be installed, EN 15251 (2006) suggests set points for existing buildings RH 20%.

High humidity level is problematic and can cause serious moisture problems for the building envelope and for indoor climate due to the growth of micro-organisms and house dust mites.

There is sufficient evidence of an association between exposure to a damp indoor environment and upper respiratory tract symptoms: nasal congestion, sneezing, a runny or itchy nose, and throat irritation (IOM 2004), as well as worsened PAQ (Fang, Clausen, and Fanger 1998; Fang et al. 1999). Bornehag et al. (2001, 2004) found in their review that 'dampness' in buildings appears to increase the risk of a number of health effects, mainly respiratory symptoms (coughing, wheezing and asthma), but also other health effects, including non-specific symptoms such as tiredness and headaches. Even the ultimate lower surface RH for the germination of fungi is found to be in the range of a surface RH of 62–65%; fungal growth experiments on common building and finishing materials indicate that susceptible surfaces can be kept free of fungal growth if the RH is maintained below a surface RH 80% (Adan 1994). House dust mites provide the predominant inhalant allergens (Zork et al. 2006). Hart (1998) and Korsgaard (1983) found larger house dust mite populations when the absolute indoor air humidity was above 7 g/kg (RH 45% at +20°C). Arlian, Neal, and Vyszenski-Moher (1999) observed the effective restriction of dust mite growth and the production of the associated allergens with the maintenance of a mean daily RH of below 50%, even when the RH rises above 50% for 2–8 hours daily.

Su (2002) investigated indoor conditions of houses with mould growth problems during winter in Auckland and reported that visible mould growth on indoor surfaces is a relatively common problem in aged residential houses that lack sufficient insulation. Critical RH level for microbiological growth is 75–95% depending on the temperature and building material (Johansson et al. 2012; Johansson, Svensson, and Ekstrand-Tobin 2013). Su (2006) showed that two possible options are available to control the mould growth in different climatic conditions and housing designs: a conventional method for buildings designed for permanent thermal active controls and a newer method using passive building design and passive controls to keep the indoor RH under 80%. The RH of the indoor air near surfaces was mainly controlled by appropriate insulation level and thermal resistance of the house envelope. To design renovation solutions, information about the current situation and hygrothermal loads is necessary. As the indoor RH depends on the indoor temperature, outdoor humidity, moisture production and ventilation airflow, presenting humidity loads by moisture or vapour excess is proposed as the most independent parameters (Kalamees 2006; Kalamees et al. 2012).

Based on the database of Estonian historic rural barn-dwellings, the renovation and reuse of old traditional historic rural houses has become more widespread during the recent decade (NHB 2014). Also, scientific interest in the sustainability of vernacular architecture has grown noticeably during the first decade of this century (Foruzanmehr and Vellinga 2011). Interest in the use of multiple criteria decision making methods has increased (Aygün 2000; Šiožinytė, Antuchevičienė, and Kutut 2014). Many etnographic and architectural studies about historic and traditional rural houses and indoor hygrothermal conditions in modern houses in colder climate regions have been published (Geving, Holme, and Jenssen 2008; Gustavsson, Bornehag, and Samuelsson 2004; Kalamees 2006; Kalamees, Vinha, and Kurnitski 2006; Kotol et al.

2014; Ruotsalainen et al. 1992). However, they lack detailed information about indoor climate conditions. In this work we present the indoor temperatures, humidity loads and user satisfaction in naturally ventilated historic houses in the temperate humid continental climate around the Baltic Sea. Knowledge about indoor climate conditions is necessary for policy and practice development regarding sustainable renovation and design of energy efficiency, indoor climate, and hygrothermal performance of historic and traditional rural houses.

2. Methods

2.1. Studied houses

Indoor climate was analysed by field measurement in 24 traditional rural houses in Estonia (EST), 20 houses in Finland (FIN) and 23 houses in Sweden (SWE) (see Figure 1). All the studied houses are located in the northern part of Dfb climate zone (humid continental mild summer, wet all year), near the Dfc climate zone in Finland (subarctic with cool summer, wet all year).

2.1.1. Estonian houses

The predominant historic farmhouse in Estonia is a barn-dwelling. Poly-functional barn-dwelling served both as a living and a husbandry building. It consists of three main parts end to end: a kiln-room, a threshing room and bedrooms. The kiln-room served as a living and working room all year round, although in autumn grain was dried there. Over the time improvements have been made to better adapt them to people's needs. At the turn of the eighteenth to nineteenth centuries, the need to build chimneys in dwellings in order to get rid of smoke was considered most urgent. The barn-dwelling was far from comfortable and cosy for people. Even the barn-dwelling corresponded to the general needs of life, though it included many shortcomings from today's people's point of view. External walls of the kiln-room and bedrooms are made of wooden logs with a thickness of 0.12–0.20 m. The houses were mainly heated with wood-heated ovens. Typically there was only passive stack ventilation and window airing.

2.1.2. Finnish houses

In Finland, the most common historic house type is a log house, which is used only for living purpose. Eighty percent of the studied Finnish houses were that type of log houses. Though built during the period 1700–1940, the basic wall structure of different buildings is similar. The cladding was made from wooden board. The most frequent floor structure is a plank floor with an outdoor-ventilated crawl space. Finnish traditional windows have two glass panes in wooden frames. Traditionally, historic houses were heated with wood-heated ovens. All the studied houses were equipped with ovens although auxiliary electric heating was installed in several houses. Renovated historic houses have quite a wide variety of heating systems, like ground source heat pump that was installed in one of the investigated houses, and two houses were heated with district heating.

2.1.3. Swedish houses

Stone houses in Gotland are usually built with the dry wall technique (limestone or sandstone stones stacked on top of each other, kept in place with smaller balance stones and without mortar). The façades are plastered and painted with lime wash in different colours. The windows are either single or double glazed. All the studied houses had fire places. Nowadays the fire places are not used as the main heating source. During the 1960s, many oil-fired boilers with

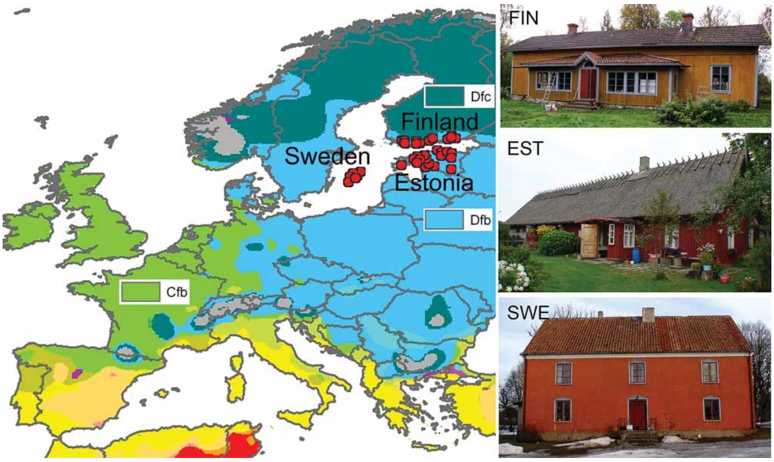

Figure 1. Studied houses from Estonia (EST), Finland (FIN) and Sweden (SWE) (right) are marked in Köppen climatic map (left; Peel, Finlayson, and McMahon 2007) with red dots.

radiator heating were added. In the 1970s, electric radiators were installed in buildings heated only by fireplaces. Due to high oil prices since the 1990s, many oil-fired boilers have been converted to burning firewood, wood pellets and wood chips or replaced with new boilers burning biofuel. Few oil-fired boilers are still left. Direct electric heating is used only if there is no hydronic system.

2.2. *Measurements of indoor climate*

In each house, indoor temperature and RH were measured continuously with data loggers (HOBO U12-013: temperature measurement range: $-20°\text{C}$ and 70°C with an accuracy of $\pm 0.35°\text{C}$; RH measurement range: 5% and 95 RH% with an accuracy of $\pm 2.5\%$) at one-hour intervals. The indoor loggers were located on separating walls or on the furniture in the height of 0.5–1.8 m from floor level. Depending on the number of rooms and their usage profile, from each house 1–5 rooms (typically main bedroom, living room, kitchen and storage) were selected in the investigation.

The vertical indoor air temperature difference between the floor and the ceiling level was measured in eight houses during one-year period. Temperature on the inner surface of the critical thermal bridge was measured with the thermistor probe and logged at one-hour intervals. Outdoor climate was measured near the studied house or climatic data were retrieved from the nearest weather station.

2.3. *Assessment of indoor hygrothermal conditions*

Indoor hygrothermal conditions were assessed separately for:

- year-round continuously used houses:
  1. temperature as a factor in general thermal comfort;
  2. indoor RH as a factor for health symptoms (dryness, primarily of the eyes, as well as of the nasal cavity, mucous membranes and skin), material emissions and mould growth;
  3. internal moisture excess as the main parameter for indoor humidity loads;
- periodically used and unused houses in winter,
  1. indoor RH as a factor for mould growth and material degradation;
  2. stability of RH as a factor for preserving materials (swelling and shrinkage) and
  3. Internal moisture excess as the main parameter of indoor humidity loads.

Indoor thermal conditions in the studied houses were assessed based on the target values from the standards (EN 15251 2006; CR 1752). The III indoor climate category (ICC) (acceptable moderate level of expectation, for existing buildings) was selected for the comparison. The indoor temperatures during heating period must be in the range of $22 \pm 3°\text{C}$. During the summer, the indoor temperature dependency on the outdoor temperature according to the standard (EN 15251 2006) was used as old houses are without mechanical cooling systems. The indoor RH values in the range of $20\% < \text{RH} < 45\%$ during winter and in the range of $30\% < \text{RH} < 70\%$ during summer were selected as target levels based on the literature review. The band inbetween winter and summer values is based on a previous study on indoor climate in Estonian and Finnish dwellings, which allows conclusions to be made that the heating season would change in summer at 15°C average daily outdoor temperature point (Kalamees 2006) and moisture excess does not change much during a cold period ($t_e < 5°\text{C}$) (Kalamees et al. 2006). The percentage of time when the criterion was exceeded was used for thermal evaluation purposes. Exceeding the target values up to 5% of time was allowed.

Old houses often contain building materials and valuable interior objects that are needed to preserve in stable climatic conditions. The variation of RH causes swelling and shrinkage of wooden objects. The daily variation of RH 10–25%, that is, the drop from 65% to 40%, was revealed as an allowable threshold. It has been found (Brown et al. 2002) that for organic materials which naturally acclimatize to a midrange RH of around 50%, a variation in RH on a daily basis of 10% represents a low risk to most organic materials, 20% is dangerous to some composite objects, and 40% is destructive to most organic objects.

Mould growth depends on many parameters, and typically high water activity of the substrate is the main reason for mould growth risk in rooms (houses). In a long-term comparison, the material is in equilibrium with the surrounding air and we can use RH to assess the water activity. Conditions favourable for initiation of mould growth on wooden materials were calculated using temperature and RH measurements from air and surfaces of the building envelope. Mould growth index (Hukka and Viitanen 1999) representing risk of mould growth was calculated in every measured room according to the indoor air and on the inner surfaces (where the temperature of the inner surface was measured). In the temperature range 0–50°C, the critical RH required for the initiation of mould growth is a function of temperature (Hukka and Viitanen 1999, Equation (1)):

$$\text{RH}_{\text{crit}} = \begin{cases} -0.00267 \cdot t^3 + 0.160 \cdot t^2 & \\ \quad -3.13 \cdot t + 100\% & \text{when } t \leq \ 20°\text{C} \ . \\ 80\% & \text{when } t > \ 20°\text{C} \end{cases} \tag{1}$$

Based on the visual appearance of the surface, the mould growth index $M = 1$ represents conditions where some mould growth can be detected only with microscopy, that is, $M < 1$ there is no mould growth on a wooden surface.

The values of the internal moisture excess, $\Delta\nu$, g/m^3 (difference between the indoor and the outdoor air water vapour content (Equation 2), were calculated on the basis of the measured results of the indoor and the outdoor temperatures and RH:

$$\Delta v = v_i - v_e, \tag{2}$$

where ν_{i} is the indoor air water vapour content, g/m^3 and ν_{e} is the outdoor air water vapour content, g/m^3.

To analyse the dependence of the moisture excess on the outdoor climate, data from each house were sorted according to the outdoor air temperature, using a 1°C step of the outdoor temperature. From each house, the average and critical values of the moisture excess from one-week periods were selected at each outdoor temperature. The higher 10% critical level (Sanders 1996) was calculated, it means that hygrothermal loads higher than the determined critical value should not exceed 10% of the cases.

2.4. *Background measurements, investigations and the questionnaire*

To obtain relevant indoor climate information, several measurements were conducted. The airtightness of the building envelope was measured with the fan pressurization method (EN 13829 2000). Places of air leakage and thermal bridges and their distribution were determined with thermography measurements (EN 13187 1998) during winter.

In each house, a building survey was carried out including the analysis of structures and service systems as well their conditions: building characteristics (construction year, building dimensions, occupants' data, etc.), the building materials used, type of the heating system of the service system (type, usage, energy consumption, problems, etc.), the ventilation system (type, usage of unit and windows), domestic hot water (type, heating, age, materials, etc.), sewerage, electricity and their use (position of fan speed during different seasons, possibility of opening windows, etc.).

In addition to the measurements, a questionnaire (6 × A4 pages) was completed about each occupant's habits and the usage of the house (installed appliances and equipment, normal presence of occupants, moisture sources, use of shower, sauna or bath, etc.), typical complaints and symptoms related to indoor air quality (too warm, too cold, unstable temperature, cold floors, too humid, too dry, draught, stuffy air, bad smell, inadequate ventilation, dust and dirty surfaces, noisy ventilation system, poor lighting, unequal temperature in the rooms, static electricity, vertical temperature gradient, noise of the heating system, etc.), occupant's opinion about renovation solutions to obtain an overview for measurements and information about user satisfaction. Answers to the questionnaire were obtained in 67 houses by interview from the occupants who acted as the contacts for the study. The answers about the indoor climate, user satisfaction ('yes' (with description, where and reasons) or 'no' answers) and construction details were collected after the measurement year in each house and were grouped, compared and analysed with indoor climate measurements. Statistically significant relations were analysed based on the student's *t*-test, where $p < .05$. The relations with less than four samples in the compared group were excluded.

The outdoor temperature and RH data were gathered from the nearest weather station, including the period from 2010 to 2012. December, January and February were considered as winter months and June, July and August as summer months. Characteristic outdoor climate values from the time corresponding to the measurement period in houses in each country are presented in Table 1.

Table 1. Characteristic parameters of outdoor climate during the measurement period.

Parameter/country	Estonia	Finland	Sweden
Average outdoor temperature in winter months (°C)	–5.5	–4.6	–0.7
Average outdoor temperature in summer months (°C)	18	18	17
The coldest monthly average temperature during winter (°C)	–12	–11	–5.6
The warmest monthly average temperature during summer (°C)	22	21	18
Lowest temperature during winter (°C)	–32	–27	–20
Average RH in winter months (%)	90	97	87
Average RH in summer months (%)	77	81	83

3. Results

3.1. *Indoor temperature conditions*

To review the thermal conditions in continuously used houses, the dependence of the hourly indoor temperature (t_{i}) on the running average outdoor temperature of previous one day (t_{e}) was analysed. Figure 2(a) shows indoor temperatures at one-hour interval during the whole measurement period. Grey dots show the results within the III ICC, while the circles show the indoor temperatures outside the target levels. From all the indoor temperatures at the corresponding outdoor temperature, the average values were calculated. Each individual thin solid curve in Figure 2(b) represents the average value from the average daily indoor temperature at the corresponding average daily outdoor temperature in one continuously used house. The dotted curves in Figure 2(b) represent the average values from all continuously used houses in different countries. The curve with circles represents the mean from stone houses in Sweden and the other two curves represent wooden houses.

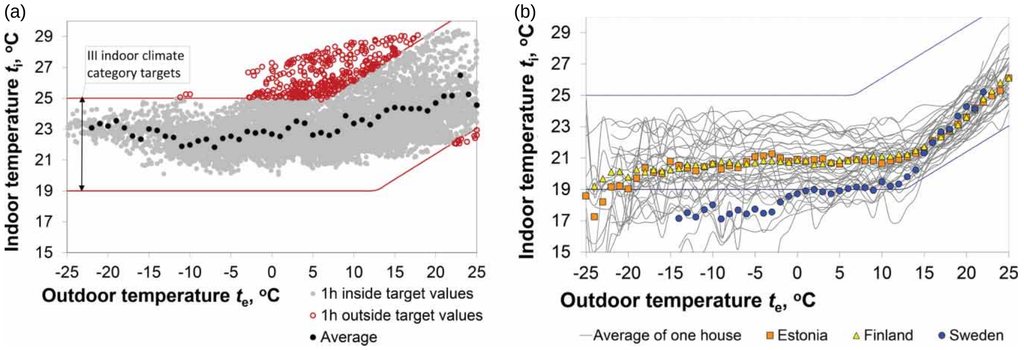

Figure 2. Dependence of the indoor temperature on the outdoor temperature in one measured house (a) and in all continuously used houses, including average values from three studied countries (b).

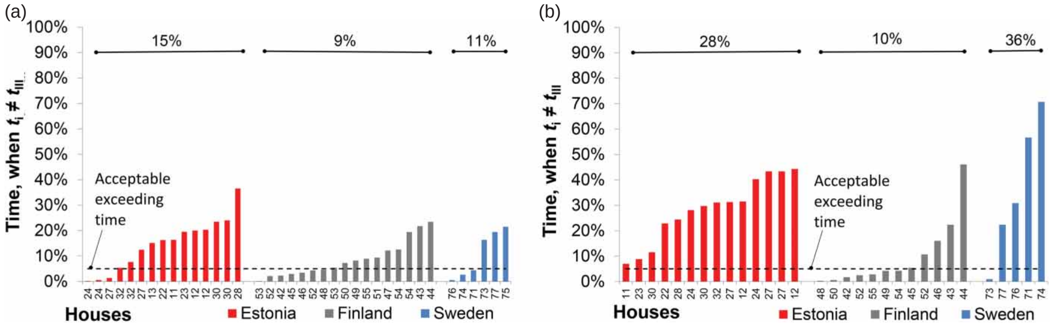

Figure 3. Percentage of time when indoor temperature (t_i) exceeds target values for indoor climate targets of the ICC III (t_{III}) in the summer period (a) and in the winter period (b) in all continuously used houses, including average values from the three studied countries.

In the winter period, the indoor temperature in continuously used houses was significantly higher (2.6°C, $p = .0004$) in Estonian and Finnish wooden houses as compared to Swedish stone houses. The reason for lower temperatures in Swedish houses is the combination of about three times higher thermal transmittance of thick stone walls (compared to wooden walls in Estonia and in Finland) and unsealed windows (in most of the Estonian and Finnish houses the windows were sealed). Sealing of windows was not related to the airtightness of the house. The average temperature in the winter period was 21.1°C in Estonian houses, 20.6°C in Finnish houses and 18.4°C in Swedish houses.

In the summer period, there is no clear difference between the countries, and all of the average values and most of the curves of the houses were in the range of the target values of the standard. The average indoor temperature in the summer period was 22.7–23.5°C without significant difference between subgroups. In Estonia, the average indoor temperature is below targets when the outdoor temperature falls below -20°C and in Sweden, the average indoor temperature falls below target values when the outdoor temperature is below 0°C. The variation of temperature is mainly caused by high air leakage rate of the building envelope and periodic heating. Inhabitants feel it as periodical (daily) low and high indoor temperatures. The average daily variation of the indoor temperature is 1.7–3.6°C in the houses used continuously all year around and 1.0–1.9°C in unheated houses. A comparison of the summer and the winter period revealed that the average variation of the indoor temperature in continuously used houses was 2.2–4.3°C during winter and 1.7–2.1°C during summer. During the winter period, the variation was 1.2°C higher in continuously used houses ($p = .001$) and 0.4°C lower ($p = .04$) in unheated houses.

Indoor temperature was compared to the target values (EN 15251 2006) of the ICC III during summer (Figure 3(a)) and winter (Figure 3(b)). The room temperature in rural houses is too low all year round: 15% of the time during winter and 12% of the time during summer. The temperature was too high in few houses: 7% of the time during winter and 26% of the time during summer. If it is acceptable to exceed the indoor climate target values by up to 5% of the time, then the indoor temperature will not meet the ICC III values in 63% of all continuously heated houses during summer and in 71% during winter (Figure 3). The correspondence of the indoor thermal conditions to the target values is similar when comparing

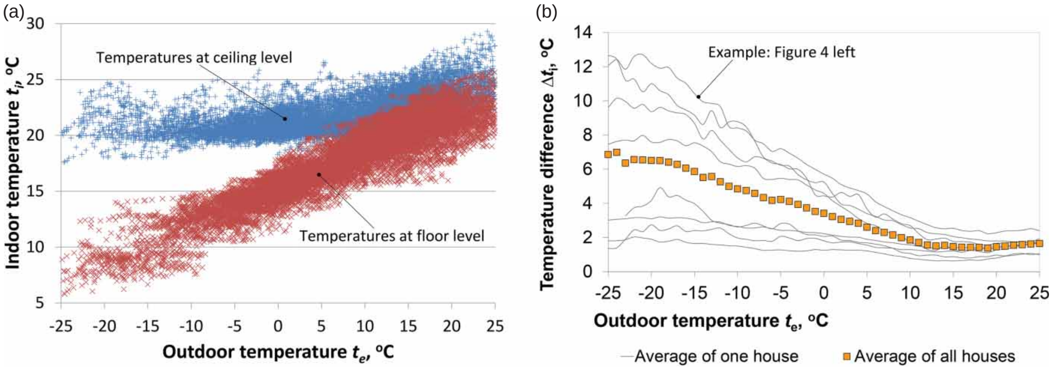

Figure 4. Example of indoor temperatures monitored at the floor and the ceiling level as a function of the outdoor temperature (a). Vertical temperature difference as a function of the outdoor temperature in the eight measured houses (b).

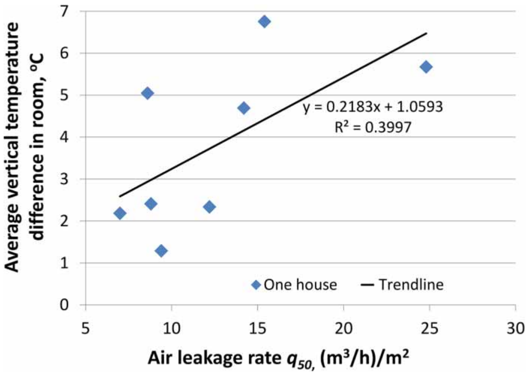

Figure 5. Correlation between air leakage rate of the building envelope and the average vertical temperature difference during winter months (December, January and February).

the winter period and the whole year, during the summer period the correspondence is better (during the summer period indoor temperatures out of target values show twice lower occurrence than those during the winter period) in the studied houses in Estonia and in Sweden, in Finland the target values are not met during 9–10% of the time all the year around.

To review vertical temperature differences in the rooms, an example of the monitored temperatures as a function of the outdoor temperature is shown in Figure 4(a) and the temperature differences in the measured houses are shown in Figure 4(b).

Figure 4 reveals that the vertical temperature difference in the room is strongly influenced by the outdoor temperatures. Comparison of airtightness of the building envelope and the vertical temperature difference between the floor and the ceiling level showed that leakier houses had also larger vertical temperature difference. One reason for the high vertical temperature difference in a room is the high air leakage rate, and correlation on the cold period based on the current study is shown in Figure 5, although the graph is similar all year round. Each point in Figure 5 represents one measured room in one house where air leakage rate and air temperature on the floor level and the ceiling level were measured. The vertical axis shows the average temperature difference between the two measuring points during the winter period and the horizontal axis represents the air leakage rate q_{50}. Cold air is infiltrating the building from the floor level and is heated up inside the building. The neutral pressure level is located somewhere between the floor and the ceiling height. In the upper part of the building an overpressure occurs, which is driving the warm air out through the leakage paths in the upper structures. The leakier the building, the stronger the driving force.

3.2. *Indoor humidity conditions*

The dependence of the indoor RH on the outdoor temperature was analysed similarly to the indoor temperature (Figure 6). Most of the average values of RH were in the range of the target values (20–45% during winter and 30–70% during summer). Only on extremely cold periods, it may be too dry and in spring or in autumn too humid in some houses. Though there were differences in temperatures, there were no significant differences in humidity levels between wooden houses in Estonia and stone houses in Sweden. However, there was a significant difference ($p < .05$) between the wooden houses in Finland and in Estonia: indoor RH was about 2% lower all year round in Finnish houses compared to Estonian wooden houses. The average RH in the winter period in Estonian houses was 35%, in Finnish houses – 34% and in Swedish houses – 40%. The indoor RH in the summer period was 60% in Estonian houses, 55% in Finnish houses and 60% in Swedish houses.

Plastered external walls caused ∼5% higher indoor RH all year round in Estonian and Finnish houses ($p = .04$ in summer and $p = .05$ in winter). When Swedish houses were included (all plastered stone walls), then p-values

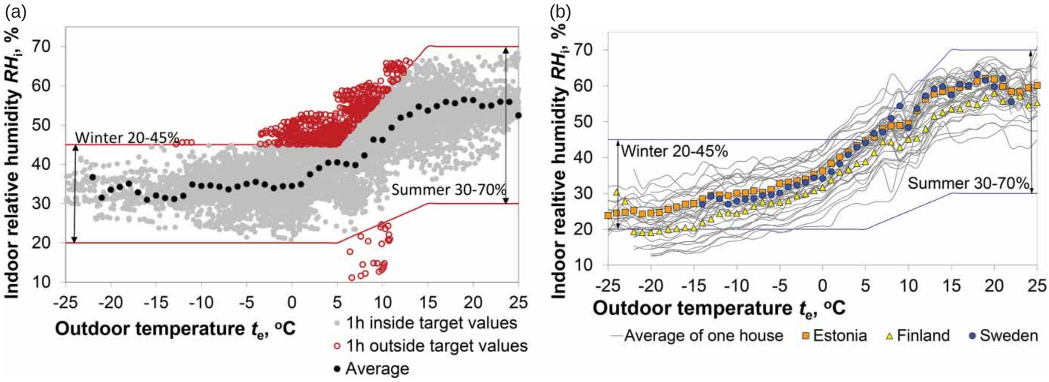

Figure 6. Dependence of the indoor RH on the outdoor temperature in one house (a) and in all continuously used houses, including average values from the three studied countries (b).

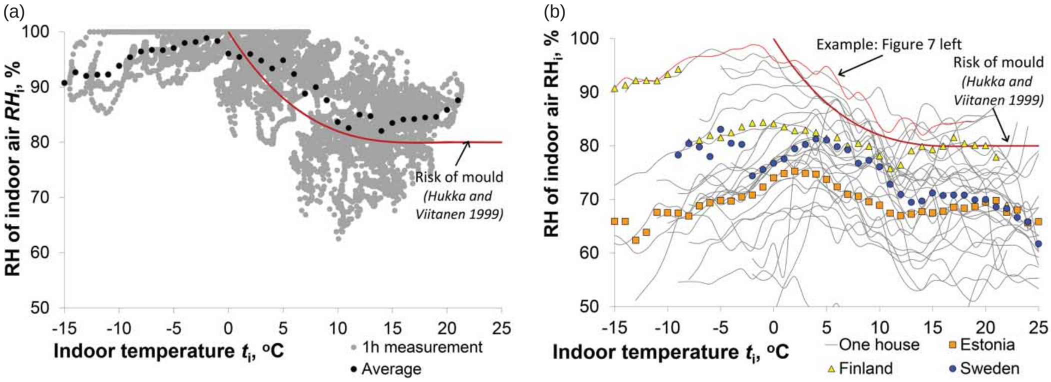

Figure 7. Dependence of the indoor RH on the indoor temperature and risk for mould growth in one house (a) and in all unheated houses, including average values from the three studied countries (b).

were even smaller (.02 and .008, respectively). The higher indoor RH was mainly caused by lower indoor temperatures (described in the previous section) and also influenced by higher moisture loads (described in Section 3.3).

3.2.1. *The risk for mould growth indoors*

RH was high in almost all unheated houses (Figure 7) and in many periodically heated houses. The critical RH for mould growth depends also on the temperature (Hukka and Viitanen 1999). Periods with high RH and very low temperature are not critical for mould growth. The average indoor temperatures in periodically heated and in unheated houses are lower than in continuously used houses even in the summer period.

Mould growth risk existed in 17% (11 houses) of all the houses and 33% of the unheated houses, Figure 8(a).

In Estonia, the temperature of the inner surface of the joint of the external wall and the base floor was measured in 15 houses. According to the indoor air moisture content, the RH and the mould growth index on that surface were calculated, Figure 8(b). Twenty-seven percent (4 houses) of the measured houses had mould growth risk, including 2 continuously used houses and 2 unheated houses. Mainly, the risk was caused by the thermal bridge or the air leakage place.

3.2.2. *Stability of indoor humidity*

The stability of indoor RH is important, because historic houses could contain valuable interior and wooden objects. The average daily variation of the indoor RH is 5–6% in all year around continuously used houses (Figure 9(a)), it means that it is not related to outdoor climate. In unheated houses, the average daily variation of the indoor RH is 2–4%, that is, about two times lower during the winter time than in heated houses (Figure 9(b)). The comparison of the summer and the winter period showed that during summer the average variation of the indoor RH is 1.5–2.1% higher ($p = .004$ in continuously used houses; $p = .07$ in periodically heated houses; $p = .0002$ in unheated houses), but still in unheated houses the variation is smaller (Table 2).

Average daily RH variation stayed almost always below 10%: 3.0–5.0% during winter and 5.1–6.5% during

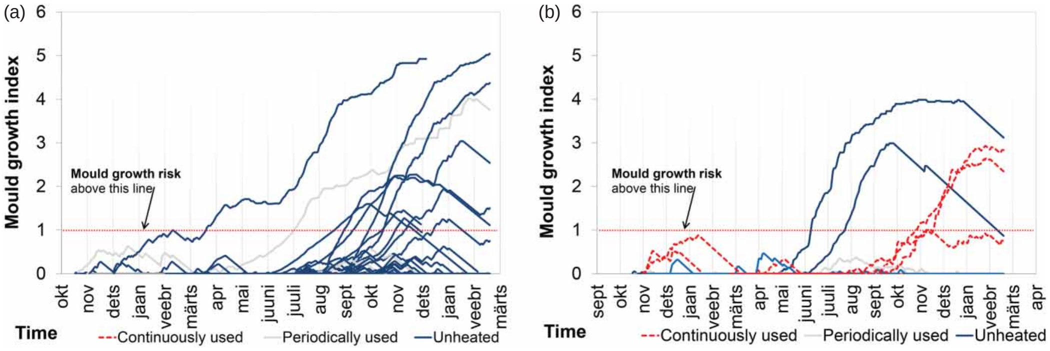

Figure 8. Mould growth index in the indoor air (a) and at the inner surface of the joint of the external wall and the base floor (b) in continuously used, in periodically used/heated and in unheated houses.

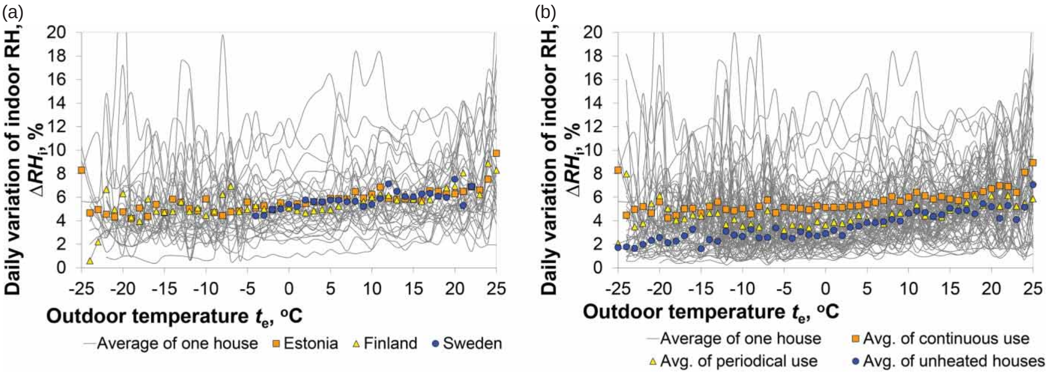

Figure 9. Average daily variation of the indoor RH in different countries in continuously used houses (a) and in all houses with different usage profiles (b) as a function outdoor temperature.

Table 2. Average daily variation of indoor RH (%) during the measurement period.

House selection/season	Summer	Winter
Estonian houses	5.1	3.7
Finnish houses	6.8	5.2
Swedish houses	6.1	3.6
Continuously heated houses	6.5	5.0
Periodically heated houses	5.5	3.8
Unheated houses	5.1	3.0

summer. According to a previous study (Brown et al. 2002), there is a low risk of damages to most organic materials (in only couple of cases it can be dangerous to some composite materials) caused by swelling and shrinkage due to the variation of RH in naturally ventilated historic rural houses.

3.3. *Indoor humidity loads*

The internal moisture excess was selected as the main parameter of indoor humidity loads. Significant ($p < .01$) differences were found in indoor humidity loads in different houses based on the usage (Figure 10). Comparison of the houses based on their usage profile showed that the highest average moisture load was in continuously used houses (2–3 g/m^3) and the lowest in unused houses (0.5–1 g/m^3), Figure 10(a). The moisture excess from the inhabitants in the period when a house is not used should be zero, and higher values in unused houses during winter are caused by drying out of constructions. During the summer period, the moisture excess was similar at all house usage profiles (between -1 and 1 g/m^3). During the winter period, the moisture excess was higher in houses with higher occupancy: in continuously used houses 1–4 g/m^3, in periodically used houses 0–3 g/m^3 and in winter in unused houses 0–1 g/m^3. Figure 10(b) shows the 10% higher critical level, which means that hygrothermal loads higher than the determined critical value should not exceed 10% of the cases.

Significant ($p < .01$) differences were also found when comparing continuously used houses in Estonia and Finland or Sweden. The differences between the countries were caused by a combination of factors such as

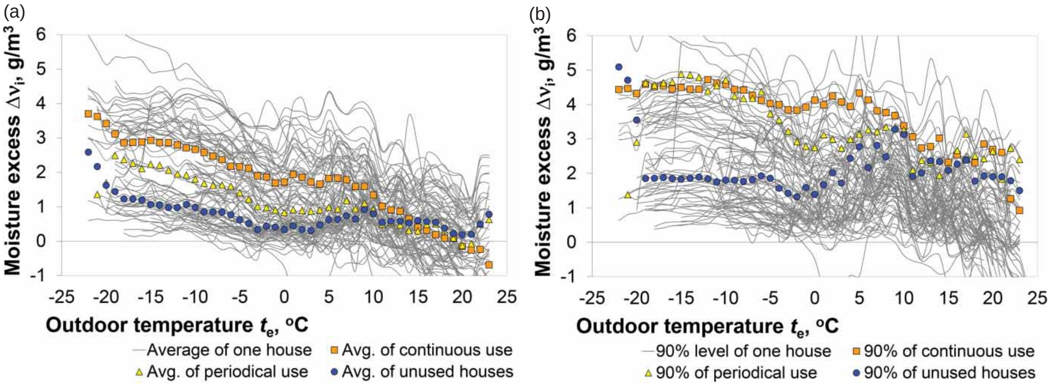

Figure 10. Weekly average (a) and 90% level (b) of moisture excess in all measured houses according to the usage profile.

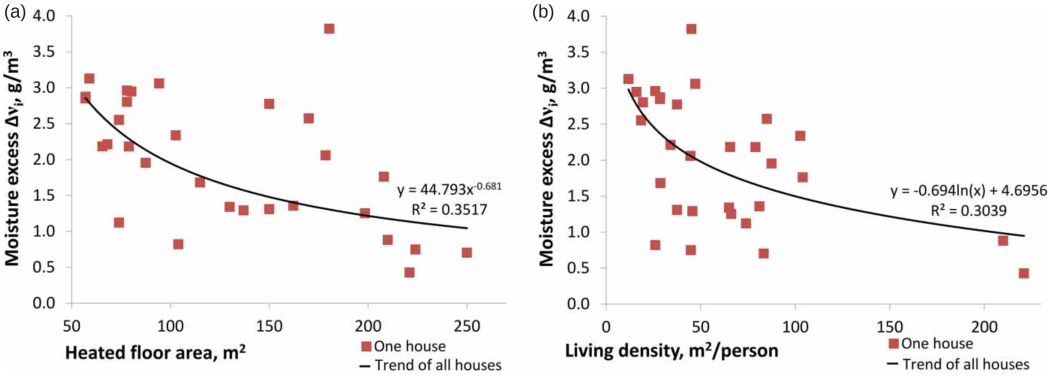

Figure 11. Indoor moisture excess during winter and heated floor area (a) or living density (b).

mechanical ventilation, heating system, airtightness of external envelope, heated area and living density. The highest average moisture load in continuously used houses was in Estonia (2.5–3.5 g/m^3) and the lowest in Finland ($\sim$2 g/m^3). Due to the small number of continuously used houses analysed and high variance of factors, no further conclusions were made.

As the size of the family and the size of the house were not connected to the moisture production, the moisture production can be assumed similar in all houses. Median heated floor area of houses was 110 m^2 and median living density was 2.2 inhabitants per 100 m^2 (average 2.6). Based on Figure 11 and Table 3, a larger house has a lower moisture excess (Figure 11(a)), and moisture excess is higher in smaller houses with higher living density (Figure 11(b)).

Table 3. Significant parameters influencing moisture excess (g/m^3) in houses.

Criterion	Value	*p*-value[a]
Moisture excess in a large house ($>$110 m^2)	1.4	.01
Moisture excess in a small house ($<$110 m^2)	2.5	
Higher living density ($>$2.2 inhabitants per 100 m^2)	2.4	.004
Lower living density ($<$2.2 inhabitants per 100 m^2)	1.6	

[a] Moisture excess values of two house groups were compared with student test.

3.4. *User satisfaction*

User satisfaction with the indoor climate and the main problems are presented in Figure 12. Statistically, significant relations were found between the measured indoor climate-related parameters and user complaints about the indoor climate by the student's *t*-test analysis. Based on Figure 12, main complaints were related to unstable or too low air and surface temperatures.

Significantly ($p = .02$) higher reporting by inhabitants concerned the condensation on windows in houses that had lower correspondence of indoor temperatures to target values (III ICC in EN 15251 2006; CR 1752). Condensation

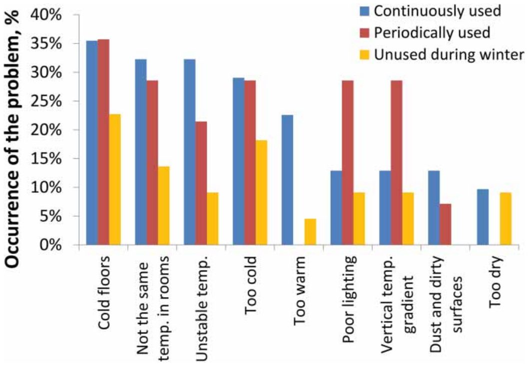

Figure 12. Occurrence of indoor climate problems in all houses.

Table 4. Significant parameters influencing user satisfaction.

Problem	Measured parameter	Value[a]	p-value[b]
Need for additional thermal insulation of the external walls	Average indoor temperature during winter months (°C)	21.3 (19.8)	.05
Smaller houses cool down faster in case of periodical heating	Daily indoor temperature variation (°C)	3.5 (2.2)	.03
Too high indoor temperatures	Air leakage rate $q_{50}[\mathrm{m}^3/(\mathrm{h{\cdot}m}^2)]$	19.1 (12.5)	.01
Indoor temperature is unstable	Air leakage rate $q_{50}[\mathrm{m}^3/(\mathrm{h{\cdot}m}^2)]$	17.3 (12.5)	.05

[a] Measured parameter value when a problem existed in house (value otherwise).

[b] Values of houses where a problem existed and houses without problem were compared with student test.

on windows depends on several factors: thermal transmittance of window, interior surface resistance, indoor humidity loads, indoor and outdoor temperature conditions. Decrease of indoor temperature decreases, also window's surface temperature that could decrease below dew point temperature. With leaky windows, interior surface of window is cold and temperature may decrease below dew point temperature. Leaky windows influence also temperature correspondence to target values.

To compensate the decrease of thermal comfort due to the lower inner surface temperatures of external walls, rooms were heated to a higher temperature. The average indoor temperature during winter months was 1.5°C higher when the inhabitants reported the need for additional thermal insulation of the external walls (Table 4). Smaller houses (below median of 110 m^2) tend to cool down faster on periodical heating due to the relatively larger area of the building envelope and it caused 1.3°C higher daily indoor temperature variation (Table 4).

In 50% of the houses with periodical stove heating, there were complaints about unstable indoor temperature. This complaint was registered in 90% of the houses with stove heating. The heat loss due to the higher air leakage rate of the house resulted in low indoor temperatures in the mornings. To avoid low temperatures in the morning, inhabitants heated more, which resulted in periodic overheating. It was found that when the inhabitants reported too high indoor temperatures, the air leakage rate q_{50} was 53% higher and when the inhabitants felt that the indoor temperature was unstable, the air leakage rate was 38% higher (Table 4).

4. Discussion

The current study included a questionnaire survey and physical parameter measurements as recommended by Sakhare and Ralegaonkar (2014) for the analysis of the overall indoor environment quality in dwellings and offices. Based on many studies, Sakhare and Ralegaonkar (2014) concluded that the most important parameters to achieve a comfortable indoor environment are temperature, acoustic, visual, and air quality. In this study, visual parameters were left out, other parameters were covered in the questionnaire and temperature and humidity conditions were measured. Therefore, the indoor hygrothermal conditions were assessed based on both measurements and the survey. The inhabitants did not report any acoustic problems and therefore these measurements were not needed.

In the current study, the houses were compared to the standard (CR 1752; EN 15251 2006) targets. It could be a challenge to combine today's residents' views about comfortable indoor climate and possibilities of traditional rural houses where large visible changes would be avoided. The acceptance of indoor climate conditions may be achieved with a change of indoor climate conditions and/or change of views of today's residents about comfortable indoor climate. Our study showed that both have occurred. Even based on our measurements, the deviation from the indoor climate targets was large, the overall rating for the living environment from the inhabitants was positive and the inhabitants did not report any health issues affected by the house. The use of the houses is usually the most important presumption for preserving the house. Therefore, some compliance to the views of today's residents about comfortable indoor climate may be accepted.

In the studied rural houses, inhabitants accepted lower thermal comfort because of the limited capacity of building service systems, large heat losses of the building envelope, savings on energy bills, ovens not properly heated due to fire safety aspects and adaptation of current habits. Literature gives many reasons for that behaviour. Tweed et al. (2014) showed that people have different expectations to thermal comfort and therefore, it is inappropriate that temperature target values mentioned in the regulations are good for everyone: some prefer lower and some higher temperatures and others accept the temperatures in the target ranges. Han et al. (2009) showed that in the cold winter occupants' thermal sensation responses in houses of the urban area are different from those in residences of the rural area. Mean thermal sensation vote of the rural area is higher than that of the urban area at the same operative temperature. Kotol et al. (2014) showed that house owners in Greenland tend to keep temperatures low to minimize heating cost. Yu et al. (2013) showed in the thermal adaptation study with people who live in a cold climate that chronic, long-term experience without indoor heating induces adaptations that make people feel less cold and uncomfortable during cold exposures than the people who have indoor heating. Andersen et al. (2009) showed that in Denmark in addition to the outdoor temperature, the control of the heating was linked also to the presence of a wood-burning stove. Also, the change in clothing insulation has a powerful adaptive effect on indoor temperature. Clothing is an important factor in achieving thermal comfort. When occupants are allowed flexibility in their dressing pattern, varying clothing is seen as an easy, economic and effective manner of adapting to the environment (Mishra and Ramgopal 2013). Alev et al. (2014) showed that different renovation measures are possible to improve the energy performance of historic rural houses. Braubach (2009) showed in the follow-up survey after the renovation work that the thermal insulation measures that were applied resulted in significant changes in indoor thermal comfort and the perception of cold was strongly reduced in intervention dwellings.

Current study showed that the RH was high in the houses that were unheated and periodically heated during winter and caused risk for mould growth. Parmar (2005) showed that exposure to white or tan mould after visit to lakeside cottages in Northeastern Ontario may cause a flu-like illness to severe pneumonia. To avoid favourable climate conditions for mould growth, an option is to heat the house throughout the winter, controlled by a humidistat (RH $\leq$ Equation 1 (Hukka and Viitanen 1999)). The required indoor RH and temperature values can be continuously calculated based on the mould growth model on the wooden materials because of large amount of wooden surfaces in rural houses. Another possibility is to use conservation heating to decrease the indoor RH. Piironen and Vinha (2010) showed that indoor temperature 3–5 K higher than outdoor temperature eliminates mould growth risk in Finnish summer cottages. This needs a heating capacity of 5–15 W/m^2, causing energy costs of 200–600€ during the period between September and the end of May. Although there was no risk of mould growth in every room of the house, there is still high risk that mould spores can easily spread from rooms with higher RH where the mould growth risk is high to living rooms with higher indoor temperature and no mould growth risk. Liu and Nazaroff (2003) and Airaksinen et al. (2004) showed with laboratory experiments and Chao (2003) with experiments in occupied residential environments that the spreading of ambient particles including fungal (mould) spores through the cracks in different constructions is almost inevitable. When Braubach (2009) analysed housing renovation in Germany, he showed that the intervention may have had a positive impact on the reduction of dampness in indoor air.

The deterministic design level (90% percentile) of moisture excess during the winter period was 4–5 g/m^3 in both continuously heated and periodically heated houses. In houses unused and unheated during winter it was 2 g/m^3 respectively. The average moisture load (used for stochastic analysis) during the winter period was 2–3.5 g/m^3 in continuously used houses, 1–2.5 g/m^3 and in unused houses 0.5–1 g/m^3. Similar moisture excess values were measured from houses in Estonia (Alev, Kalamees, and Arumägi 2011) and in Norway (Geving, Holme, and Jenssen 2008). These values can be used in deterministic or stochastic analysis for renovation solutions for historic rural houses. Despite the periodic use of houses, the deterministic moisture load is not smaller than in continuously used houses: the moisture load in the periodically used houses during the critical moments is the same as in continuously used buildings. When using stochastic analysis, the moisture load in periodically heated houses can be assumed to be smaller because there are periods without moisture production, allowing the accumulated moisture in the structures to dry out.

Although the RH and temperature were separately measured in the bedroom, living room and/or kitchen in almost all houses, there were no significant differences found between moisture loads in different rooms. This is because the separating doors between these rooms were absent or opened most of the time, in addition to the high air leakage rate of the external envelope and the internal walls. Therefore, the air of these rooms was mixed. Like in a previous study (Geving, Holme, and Jenssen 2008), there was no significant effect of the ventilation system found in the current study, at the same time the houses were much older and the occupancy was similar and also the moisture load was similar to the results in the compared article. Therefore, the age of the house is not relevant, but the occupancy level can be correlated with moisture excess. It was shown that in houses with higher living density, there was higher moisture excess. The higher humidity loads are partly caused by relatively larger moisture production by inhabitants in houses with high living density. In larger houses with smaller living density also air change due to infiltration air is higher, lowering the moisture excess. Therefore, the performance of the ventilation system is more important in smaller houses where the moisture load is high. The good air change is reported as one reason for no humidity problem in the current condition of Greenland's houses (Bjarløv and Vladykova 2011).

After the first visit to the previously described houses it was clear that most of the houses are leaky, periodically heated with stove, without mechanical ventilation and with low level of insulation (especially below the first floor and on external walls). These problems cause high daily variability of indoor temperature and RH. Inhabitants feel these problems sometimes directly, but more often feel or see through secondary problems as dusty surfaces, dryness, condensation on windows, static electricity, vertical temperature gradient, cold floors, etc. Energy renovation of rural houses can increase the thermal comfort and alleviate the complaints of inhabitants besides reducing the energy demand of house. In many cases the high air leakage rate was compensating the lack of performance of ventilation. Inhabitants reported 'lots of fresh air' in their rural houses compared to apartments they had lived in before.

5. Conclusions

The average indoor temperature in the winter period was from 18.4°C in Swedish houses to 21.1°C in Estonian houses. High thermal transmittance of the building envelope was the main reason for lower temperatures in Swedish houses. Comparison of airtightness of the building envelope and vertical temperature difference between the floor and the ceiling level showed that more leaky houses had also a larger vertical temperature difference. Indoor RH was in the range of target values except on extremely cold days.

There is high risk of mould growth in unheated or intermittently heated houses due to the high indoor RH levels mainly during the winter period. The mould growth risk existed in 17% of all houses and in 33% of unheated houses. Mould growth risk is higher on areas with high thermal transmittance, therefore the construction rather than the usage of the house plays a major role.

Almost none of the measured houses corresponded to the target values of ICC III. The low correspondence of indoor climate to the target values in continuously used houses was mainly caused by the daily instability of the indoor temperature and the RH. Average daily RH variation was 2.2–4.3% during winter and 1.7–2.1% during summer in continuously used houses.

Measurements in the studied houses in combination with the questionnaire with inhabitants showed that the indoor climate in all historic rural houses needs improvement to achieve correspondence to the modern criteria for general thermal comfort. As the questionnaire revealed some problems with local thermal comfort (cold floors, vertical temperature difference), this topic should be addressed in more detail in the future studies. Our comparison of continuously used houses with unheated houses or periodically heated houses showed that similar problems occur but the significance and time of occurrence are different. The main problems in order of importance were cold floors, unequal and unstable room temperatures, too low or too high indoor air temperatures, poor lighting, vertical temperature gradient, dust and dirty surfaces and too dry air; other reported issues were less common.

To obtain more stable indoor climate, the heating system should be renovated or replaced and a ventilation system with heat recovery installed. Even though building service systems are renovated, problems such as cold floors, draught or vertical temperature gradient still prevail. To eliminate these, air and vapour barrier and thermal insulation have to be installed on external walls and ceilings, and floors have to be renovated.

The average moisture load during the winter period in continuously used houses was 2–3.5 g/m^3 and in unused houses 0.5–1 g/m^3 and the corresponding higher 10% critical level during the winter period in continuously used houses was 3.8–4.7 g/m^3 and in unused houses 1.3–1.9 g/m^3. Larger houses with lower living density showed lower moisture loads. In houses without usage during winter there are still indoor humidity loads due to drying of structures.

Based on the questionnaire, the main problems were related to unstable or too low (surface and indoor) temperatures. Indoor temperature could be easily regulated with the length of heating and no temperature regulation related complaints were recorded. According to the results from the questionnaire and climate measurements, it can be concluded that the inhabitants have well adapted to lower temperatures and are considering the overall indoor climate good.

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PAPER III

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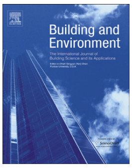

Avoiding mould growth in an interiorly insulated log wall

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ABSTRACT

Interior thermal insulation in a cold climate is risky from a hygrothermal point of view. Designers and customers are looking for solutions that provide a moisture-safe design. Avoiding mould growth in wall structures is the primary design criterion when planning to add interior insulation to a log wall. In this study indoor humidity load, average indoor temperature, the thickness of a log wall and additional insulation layer, the initial moisture content of logs and the vapour diffusion thickness of a vapour barrier were varied and mould growth risk was identified. In general, our results showed that a water vapour barrier with an equivalent vapour diffusion thickness of 2 m or more is acceptable when indoor moisture excess is up to 5 g/m^3 during winter. In these conditions, the maximum measured moisture content of logs before insulation should be below 12% and the thickness of interior insulation of mineral wool can be up to 50 mm. The water vapour resistance of a vapour barrier depends on the use of the house (for general living or as a summer cottage) and indoor humidity load. It is necessary to install a vapour barrier covering interior insulation carefully to avoid air leakages through it. If an improved vapour barrier and decreased indoor moisture excess are used, then the thermal resistance of an additional internal insulation layer can be more than double of the thermal resistance of the log wall before adding the insulation, otherwise both thermal resistances should be equal.

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1. Introduction

Log houses of different sizes were common in the Baltic and Nordic countries a century ago. Often these old log houses are still in use. Now, log houses are gaining popularity because of low embodied energy, and they are still a usable building type. Designers and owners of wooden log houses need correct insulation solutions to improve the energy efficiency and thermal comfort of their houses. A need for additional interior insulation exists in old houses when a house is a cultural heritage monument or is located in an area where it is required to preserve the exterior appearance of the house. When an architect or the owner of a new log house wants to expose the natural surface of a log wall on the exterior side, a solution to consider might be interior insulation. This solution may be also used in apartment buildings, built of wooden logs, if only a few owners want or can carry out deep renovation with additional thermal insulation. In such cases, an insulation layer from the inside room by room is an easy solution that is the most appealing one visually.

In addition to traditional mineral wool insulation, there also exist other materials used for interior thermal insulation: calcium silicate board [1], polyisocyanurate board [2,3], perlite-based board [4], wood fibre board [5], expanded polystyrene [6,7], aerogel [8], vacuum insulation panels (VIP) [9], and hydrophilic mineral wool [10]. Materials may be grouped by hygrothermal performance as vapour-tight or open to water vapour diffusion, capillary active or non-capillary active. All these properties strongly affect the performance of interior insulation. Vereecken and Roels [11] have compared the hygric performance of massive masonry walls provided with capillary active as well as more standard non-capillary active insulation systems and showed that stored moisture inside walls with a capillary active system is higher than for walls with a traditional vapour-tight system. Guizzardi [12] has evaluated the use of insulating aerogel plaster as an interior insulation layer on a masonry wall with a façade worth preserving. Based on her simulations, walls with internal aerogel plaster show a hygrothermal behaviour that is similar to the behaviour of walls retrofitted with other vapour insulation materials, such as calcium silicate, but have better thermal insulation efficiency.

Interior thermal insulation in a cold climate is risky from a moisture safety point of view. In general, the risk of failure will be higher if thicker interior insulation layers are used. The risk of

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interior insulation failure means possible mould growth in the wall structure, spread of mould spores, moisture accumulation or water vapour condensation. Spores in indoor air may cause health problems for inhabitants.

Ibrahim et al. [14] have shown that interior thermal insulation systems can cause several moisture problems: inability to dry out over the years, condensation risk, etc. Pasek and Kesl [13] have shown that the interior insulation of the perimeter building envelope in the climatic conditions of Central Europe is quite unsuitable because of a high probability of damage to the structural system of the building compared to other possible varieties of perimeter wall designs. Pašek has also shown that stress increases in external walls and adjacent structures caused by non-forced effects of temperature changes in the environment after the application of internal insulation [17]. Bjarløv et al. [15] and Finken et al. [16] have shown problems with interior insulation in masonry walls without any additional driving rain protection.

A lot of the latest research is concentrated on the hygrothermal performance of wooden beam ends in an internally insulated masonry wall. Guizzardi et al. [18] have shown that an interior insulation layer results in higher damage risk compared to a non-insulated wall, and in case of internally insulated masonry walls with timber beams, exterior render properties have the biggest effect on the risk of damage to a wall (more so than the choice of the interior insulation material). Johansson et al. have investigated the hygrothermal performance of a brick wall with wooden beam ends after its insulation on the inside with VIPs [19] and have shown reduced temperatures and higher relative humidity in wooden beams after the addition of VIPs [9]. Harrestrup and Svendsen [20] have investigated the risk of mould growth in wooden beams and in the interface between interior insulation and a brick wall in case of various insulation strategies and have recommended that internal insulation not be applied on north-orientated walls since drying potential is reduced, while for a wall facing west, a solution with a gap above or below the floor/ceiling seemed to be moisture-safe. Also Morelli and Svendsen [21] have shown that the risk to incurring moisture problems at wooden beam ends can be resolved by not insulating the portion of the wall directly above or below the floor division.

Most of the above studies investigated the options and limits in the use of interior thermal insulation for improving the thermal resistance of old external walls made of stone. Wooden structures have been investigated much less. Ojanen [22] has studied interior insulation using a theoretical calculation model and assumed that a log wall is completely airtight; however, vertical air channels between the log and the insulation layer were suggested to reduce moisture levels. Arumägi and Kalamees [23] and Alev et al. [24] have measured old log walls with a high leakage rate and created a respective calculation model. Arumägi and Kalamees [23] measured a house with a high indoor moisture load, whereas Alev et al. [24] measured one with almost no indoor moisture load. Other differences between the above studies include the type and use of a house, the insulation materials employed, hygrothermal loads etc. In a new log house built specially for testing, three different interior insulation solutions were measured and compared [25]. Mineral wool 50 mm thick and an insulation layer of cellulose fibre performed similarly, but cellulose fibre needs at least a week to dry out before being covered with a vapour barrier. It is safe to install a reed mat layer up to 70 mm thick, and a reed mat with clay plaster allows construction moisture to dry out faster. Alev et al. [25] have concluded that when choosing a vapour barrier, calculations must be made for every case and that the choice depends on the use of the house and the indoor humidity load. The energy efficiency and hygrothermal properties (including RH between a load bearing structure and insulation, among other properties) of different small test buildings, including an interiorly insulated log building, have been compared by Jakovics et al. [26]. In the same small test buildings, air tightness and air exchange rates have been measured: a log house has higher air leakage rates compared to other structure types measured [27].

Hygrothermal simulation models have been well developed during the past decade and allow an assessment of hygrothermal performance in a building envelope quite accurately. This allows the use of a stochastic simulation method developed in IEA-EBC Project RAP-RETRO [28] to evaluate and optimize retrofitting measures, including energy efficiency, life cycle costs and durability. Vereecken et al. [29] have developed a decision tool based on a Monte Carlo analysis and have shown, however, that in case of buildings sensitive to frost damage or if there are wooden beam ends capillary active systems are shifted forwards and that vapour-tight systems tend to be preferable for structures resistant to frost damage. The effect of material properties [30] or the effect of one section of a wall assembly [31] on hygrothermal performance and the performance of interior insulation [32] have been analysed using a stochastic approach. Arumägi et al. [33] have analysed the reliability of 50 mm thick interior insulation in a 145 mm thick log wall in typical indoor and outdoor climatic conditions in Estonia. Based on these stochastic calculations, at a safety margin set at the lower 0.95 confidence level, the statistical probability of mould growth is 37%.

As outlined above, interior insulation is more complex and not as hygrothermally safe as the widely used exterior insulation. Increasing the thickness of an insulation layer leads to a decrease in heat loss through the external wall. Thus, it is necessary to find a solution where both the risk of failure and heat loss through walls are minimal. A designer needs knowledge about the maximum thickness of an insulation layer and a list of other materials required. A builder needs knowledge about appropriate building technology and the time-scale for insulation works. The aim of the present study was to identify hydrothermally functioning combinations by varying the main parameters affecting the hygrothermal performance of an interiorly insulated log wall.

2. Methods

2.1. Studied wall

There are many parameters affecting the hygrothermal performance of interior insulation: thickness of an insulation layer, thickness of a log wall, air leakage rate of a log wall, indoor and outdoor climate parameters like temperature, relative humidity (*RH*) and moisture excess, water vapour transmittance of wall layers, and initial moisture content (*MC*) of logs. Main characteristics of the calculation model used in this study are shown in Fig. 1 and material properties in Table 1. The critical surface (Fig. 1) in the wall in terms of moisture safety was the interior surface of the log wall in direct contact with the insulation layer. The affecting finishing layer was always gypsum board. The air and vapour barrier provided airtightness for the wall.

The wall was considered airtight in the calculation model because it turned out during model validation that it was more critical when air leakage was excluded from the calculation model, because average RH on the critical surface was slightly over 1% higher when there was no air leakage in the model (shown in Fig. 4, the line marked with an asterisk). In practice, it is possible to considerably decrease air leakage through a log wall by using modern sealing materials and methods.

An Estonian moisture test reference year [34], critical in terms of mould growth in Estonia, was used for the outdoor climate after a validation of the model with the measured outdoor climate.

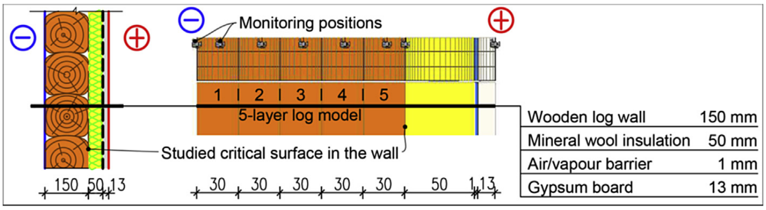


Fig. 1. Section of an interiorly insulated log wall and a screen capture of the calculation model in WUFI.

Table 1
Main properties of the materials used in the validated simulation model.

Material properties	RH, %	Materials used in simulations		
		Wooden log	Mineral wool	Gypsum board
Bulk density ρ, kg/m^3		390	60	850
Porosity f, m^3/m^3		0.75	0.95	0.65
Specific heat capacity c, J/(kg K)		1600	850	850
Thermal conductivity λ, W/(m K)		0.13	0.04	0.2
Vapour diffusion resistance factor μ, –	35	97	1.3	8.3
	60	39	1.3	8.3
	97	27	1.3	8.3
	100	27	1.3	8.3
Moisture content w, kg/m^3	33	27.3	0.23	2.4
	55	37.1	0.56	4.1
	97	81.9	11	66
	100	600	45	400
Liquid transport suction D_{ws}, (m^2/s)	33	$4.4 \cdot 10^{-11}$	–	$1.2 \cdot 10^{-10}$
	55	$5.9 \cdot 10^{-11}$		$2.1 \cdot 10^{-10}$
	97	$1.3 \cdot 10^{-10}$		$1.8 \cdot 10^{-8}$
	100	$9.2 \cdot 10^{-10}$		$4.5 \cdot 10^{-6}$
Liquid transport redistribution, D_{ww}, (m^2/s)	33	$4.4 \cdot 10^{-11}$	–	$1.2 \cdot 10^{-10}$
	55	$5.9 \cdot 10^{-11}$		$2.1 \cdot 10^{-10}$
	97	$1.3 \cdot 10^{-10}$		$3.8 \cdot 10^{-9}$
	100	$9.2 \cdot 10^{-10}$		$1.0 \cdot 10^{-6}$

2.2. *Validation of the calculation model*

Hygrothermal simulations were done with the WufiPro5.1 (WUFI) software [29].

The calculation model in WUFI was composed and validated on the basis of the field measurement data presented by Alev et al. [24]. To prepare and validate the calculation model for more comprehensive parametric calculations, field measurements were performed in an old rural house (built in 1919). The external wall was made of wooden logs. The test wall was insulated from the inside with traditional mineral wool (MW, thermal conductivity $\lambda_{MW} \approx 0.04$ W/(m K)). The internal finishing layer of the wall was made of gypsum board. Four stages of the building process are presented in Fig. 2: clean log wall with sensors on the log surface (1), mineral wool installed (2), vapour barrier installed (3) and finished test wall with gypsum board and sensors installed (4). The calculation model was validated by choosing the materials best matching those used in the measured structure from the default WUFI database and by slightly modifying the default material properties according to information identified in literature. The wood material used in the model for logs was defined in the WUFI database as "Scandinavian spruce transverse direction II", which takes into account the anisotropic properties of wood. The material properties of wood in the WUFI database were taken from a Norwegian research report [35]. Because the measured old log walls had a high leakage rate [36], air exchange through the log wall was added (air exchange was defined between the outdoor air and the mineral wool layer) to have a better match between measured and

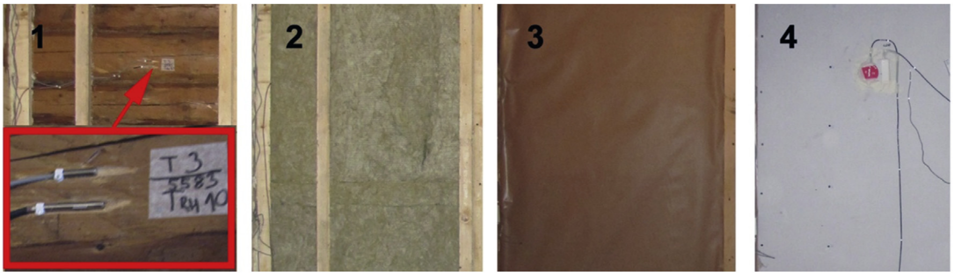


Fig. 2. Four stages the process of building a test wall for field measurements.

calculated values. Measured and calculated values of temperature and RH on the critical surface of the wall are compared in Figs. 3 and 4. On both graphs, the original calculated line, which includes air leakage, and an additional calculated line (marked with an asterisk), where air leakages are excluded, are shown. A similar calculation model has been used in another study where different insulation materials were applied to a new log house [37].

2.3. Varied parameters in simulations

The calculation results show a substantial dependence on the quality of the selected input data. It is hard to define the “average log wall” because a variety of building techniques have been used depending on the date of construction and the building traditions in different regions. In addition to building methods, building quality is also variable. It is important to take into account the variability of different parameters in real structures to ensure that the selected solution is hygrothermally safe and reliable.

To identify hygrothermally functioning boundary conditions, multiple parameters were varied, as shown in Table 2. The reference case (RC) is indicated by the greyed background in Table 2. The indoor temperature reference level is based on measurement results from previous studies [38,39], where the average indoor temperature during a cold period (outdoor temperature $t_e < 15$ °C) was 19 °C (Fig. 5A). Based on the national appendices to the standards EN ISO 13788 and EN 15026, the indoor humidity load level chosen represents an average measured level and ranges from a low humidity load ($\Delta v_i = 4/1$ g/m^3 at outdoor temperatures below +5 °C/above +20 °C) and a high humidity load in dwellings ($\Delta v_i = 6/2$ g/m^3 at outdoor temperatures below +5 °C/above +20 °C) [40,41] (Fig. 5B). Fig. 5 shows average measurement results in continuously heated and unheated houses (summer cottages) during the winter period with different dots. Continuous lines represent simplified design curves used in this study for analytical calculations. Equivalent vapour diffusion thickness (S_d) values represent the following materials: 0.01 m – no special vapour barrier; 0.1 m – similar to bitumen-impregnated paper; 1 m and 2 m – levels similar to smart vapour retarder membranes; 10 m – laminated paper; and 100 m – similar to plastic polyethylene sheeting.

2.4. Assessment of moisture safety

Moisture safety assessment was based on the risk of mould growth between logs and interior insulation. Various mould growth estimation methods have been developed [42]. Based on the comparison of these methods [42] and the authors' previous experience with the first Finnish model [43], the improved Finnish mould index (M) model [44] was used in this study. The model takes into account the material's sensitivity to mould growth (material group and surface quality), the *RH* and temperature conditions near the investigated surface (where a lower limit is described by the formula (1) below) and the duration of exposure to *RH* and the temperature conditions exceeding the boundary given by the formula (1). The lower boundary curve for the risk of mould growth in the range of temperature from 0 to 50 °C for a wooden material can be described by this polynomial function:

$$\mathrm{RH_{crit}} = \begin{cases} -0.00267\cdot \mathrm{t}^3 + 0.16\cdot \mathrm{t}^2 - 3.13\cdot \mathrm{t} + 100 & when\ \ t \le 20\,^\circ\mathrm{C} \\ \mathrm{RH_{min}} & when\ \ t > 20\,^\circ\mathrm{C} \end{cases} \tag{1}$$

where *t* is the temperature on the investigated material surface (°C), and RH_{min} represents the minimum level of *RH* at which mould growth is possible (80% for wood).

The temperature and *RH* hourly output from the simulations was post-processed, and *M* was calculated for the critical surface in the wall based on the improved M calculation model [45]. *M* represents the possible level of mould growth on a wooden surface according to the following numeric scale [46]:

1 <1 – no growth;
2 – small amounts of mould detected only with microscopy;
3 – moderate growth detected with microscopy (coverage <10%);
4 – some growth detected visually (coverage 10%–30%), spores produced;
5 – moderate growth detected visually (coverage 30%–70%);
6 – plenty of growth detected visually (coverage >70%);
7 – very heavy and tight growth detected visually (coverage 100%).

The log wall was defined as pinewood (timber species W = 1) with a kiln-dried surface quality (term for surface quality SQ = 1) and a “very sensitive” sensitive class. *M* below 1 (no growth) was considered moisture-safe, and these structures and indoor climate combinations were suggested (indicated by green colour in the results). Unacceptable solutions ($M > 1$) were presented by two colours: $1 < M < 3$ by yellow and $M > 3$ by red.

Finnish mould growth models have a few shortcomings: typical finishes of wood are not investigated; temperatures under 0 °C are not investigated and delay is not tested with long periods (>14 days). It should be noted that a decrease in mould index under unfavourable conditions probably does not improve the visual appearance of a surface.

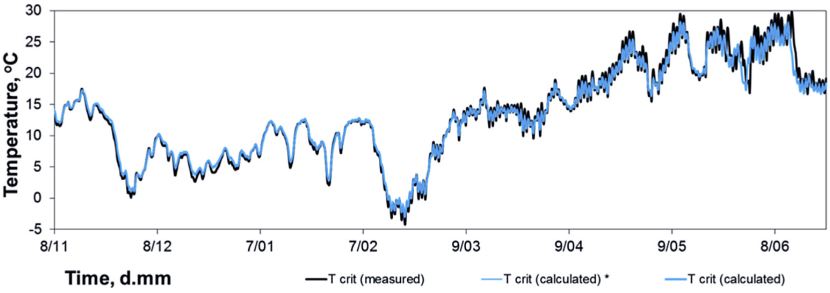


Fig. 3. Validation of the temperature on the critical surface: measured and calculated in WUFI. Calculated temperature (T) marked with an asterisk represents temperature when air leakage was excluded.

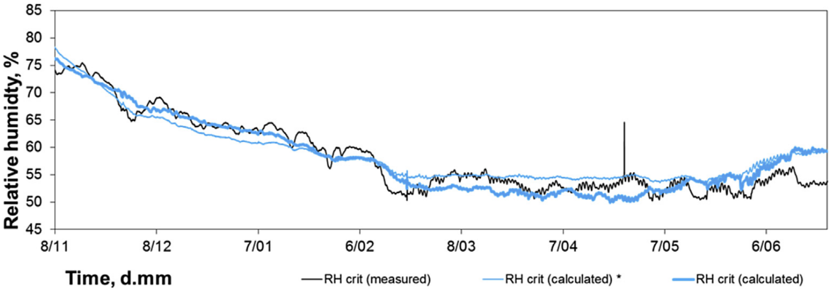


Fig. 4. Validation of relative humidity on the critical surface: measured and calculated in WUFI. Calculated RH marked with asterisk represents RH when air leakage was excluded.

Table 2
Varied parameters in the simulation model.

Parameter	Reference	Versions (values)					
Indoor humidity load Δv, g/m^3; $t_e < +5$ °C/$t_e > +20$ °C	5/1.5	1/−0.5	2/0	3/0.5	4/1	5/1.5	6/2
Average indoor temperature during winter t_i, °C	19	18	19	20	21	22	23
Thickness of a log wall d_{log}, mm	150	100	125	150	175	200	225
Thickness of additional insulation d_{ins}, mm	50	25	50	75	100	125	150
Initial *MC* of logs *w*, %	14	14	15	16	17	18	19
Vapour diffusion thickness S_d, m	2	0.01	0.1	1	2	10	100

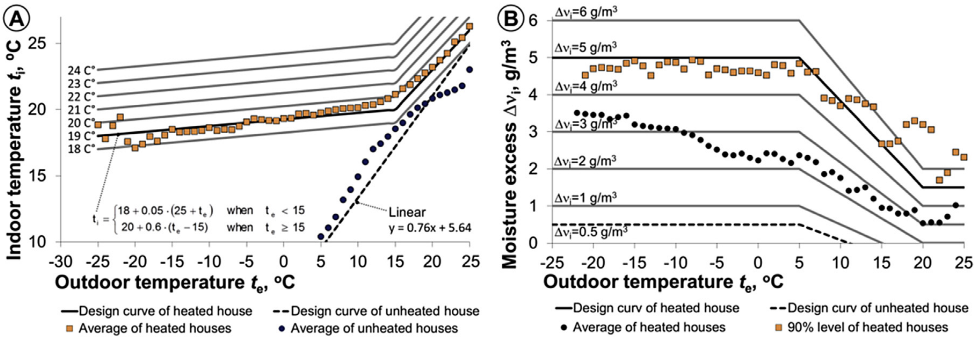


Fig. 5. Dependence of the indoor temperature on the outdoor temperature in wooden houses (A); and 90% level of weekly maximum moisture excess at the corresponding outdoor temperature (B).

2.5. Simulated cases

First, before starting interior insulation work in the desired month, we checked whether it was hygrothermally safe. The objective was to identify the month during which built-in moisture levels in a log wall are minimal. Over the course of a year, indoor and outdoor *RH* changes and affects the moisture content in a log wall. 12 year-long simulations were made, with the start time matched to the beginning of each month. The structure consisted of a 150 mm thick log wall only, divided into five equal 30 mm thick layers (Fig. 1A, without any insulation). The outside was exposed to the outdoor climate, whereas the inside was exposed to either a free-floating climate (representing an unused house or a summer cottage before renovation) or a warm climate (representing continuously heated houses). Design curves for both cases are shown in Fig. 5.

Secondly, the drying-out time of built-in moisture was analysed. The calculation period started at the beginning of June. Both unheated (summer cottage) and heated (regular house) cases were analysed. The indoor temperature of unheated houses was chosen based on the measurement results from Alev et al. [38]. The design curve with the formula for unheated houses is shown in Fig. 5A. In winter, based on the same study [17], Δv_i in unheated houses was chosen to be 0.5 g/m^3. In a heated case, the average indoor temperature in heated houses was used and $\Delta v_i = 5/1.5$ g/m^3. The log wall was considered with a constant *MC* at the beginning of the calculation period. The *MC* in logs was varied from 14% to 19% with a 1% increment.

A parametric study was conducted to analyse the risk of mould growth on the critical surface: the inner surface of a log. One parameter (Section 3.3) was varied at the same time, with the other parameters being based on *RC*. The output was given as *M* change over five years (line). When two or three parameters were varied (Section 3.4), the output was given in a tabular form, showing the maximum mould index *M* value for each combination over five years. A period five years long calculated with the moisture test reference year was considered long enough to achieve stable yearly hygrothermal variation with most of the calculated combinations. The mould growth index over the five-year period is probably overestimated because the same critical year for mould growth is used repeatedly, which is unlikely to occur in practice.

3. Results

3.1. Effect of the start time of renovation works

Based on our experience, home owners often start major renovation works at the beginning of summer (May to June) because during the summer the outdoor climate is more convenient for builders. In case of a continuously heated house, when only interior insulation works are planned, the outdoor climate (and therefore the preferred season for insulation works) is irrelevant. Fig. 3 presents results for the start of renovation: each line represents the average moisture content at a given depth from 12 simulations. The *MC* curves for each of the months mainly overlap.

The highest fluctuation in moisture levels in an unheated house occurs in the outer layer (layer 1): from 12% in May to 17% in February (Fig. 6A). In a heated house, MC is only up to 0.5% lower during winter (Fig. 6B). A 30 mm thick layer next to the outer layer (layer 2) has significantly lower MC fluctuation: from 13% in August to 15% in March (Fig. 6A). In the central layer (layer 3), moisture levels are the stablest: from 13% in autumn to 14% in spring (Fig. 6A). The moisture content in layers 2 and 3 in a heated house is slightly higher during winter (Fig. 6B). The MC in layer 4 is 1% lower than that in layer 3 during spring and summer but similar during autumn and winter months (Fig. 6). The innermost layer (layer 5) shows higher fluctuation and the highest difference between an unheated and a heated house. The MC in layer 5 ranges from 11% in summer to 14% in spring. During winter, MC in layer 5 is 11% in a heated house and 13% in an unheated house. It may be concluded that the average MC in a log wall (Fig. 6) is the lowest during summer months (minimum of 13% in July) and the highest during winter months (a maximum of over 14% in February). Diffusive moisture transport in wood is a slow process, as the time interval between the peak points in the surface layer and in the middle layer is at least three months. It means that diffusive moisture flux takes at least six months to penetrate a 150 mm thick log wall.

The maximum mould index *M* values on the critical surface were below 1 in all the previously calculated months in both heated and unheated houses. It is safe to install an internal insulation layer all year round but it is safer from May to August when the average *MC* of the wall is lower. It also matches owners' renovation time preferences.

3.2. Drying-out of built-in moisture

Fig. 7 shows the drying-out potential of an interiorly insulated log wall in an unheated and in a heated house over the course of five years. Fig. 7C indicates that in the absence of a special water vapour barrier, the wall of an unheated house with low $\Delta \nu_i$ will dry to 14%–15% in two years. If a wall structure without a vapour barrier is in a heated house with $\Delta \nu_i = 5/1.5$ g/m^3, *MC* keeps rising over the course of years. With an average vapour barrier (used in *RC*) in a wall structure, the wall keeps drying in both heated and unheated houses, as indicated in Fig. 7A. In an unheated house, $\Delta \nu_i$ is lower, and therefore after five years the *MC* in an unheated house (14%–15%) is 1% lower than in a heated house (15%–16%) with a higher $\Delta \nu_i$. With a very vapour-tight barrier (Fig. 7D), drying takes longer, and the influence of $\Delta \nu_i$ is insignificant. In a heated house, drying is faster, and after five years, *MC* is about 13% and in an unheated house, between 14% and 15%.

In a heated house, moisture levels in the inner layer will decrease faster; in the middle layer, however, no significant difference was found between a heated and an unheated house. It takes at least two times longer to dry a log wall interiorly insulated and covered with a vapour-tight barrier than to dry a log wall without any insulation. If at the beginning the built-in moisture level is 14%, it will not decrease in a cold house in one year; rather, it will increase during winter. When moisture levels are higher at the beginning, decrease will also be higher during the first few months (summer months). In spring (from March), moisture levels decrease in all cases.

Fig. 7B presents the surface temperature and relative humidity curves at the critical point in the wall (Fig. 1) as calculated under the conditions of RC throughout the year. This figure also confirms lower moisture levels and higher temperatures during summer, resulting from a lower mould growth risk.

3.3. A single-parameter study of mould risk

Figs. 8 and 9 below present the mould index, depending on time, over the course of five years, where M level 1 is marked with a red dotted line, below which safe values occur.

The initial moisture of a log may be the dominant moisture source for an interiorly insulated log wall, in particular when the assembly is equipped with a tight vapour barrier. Fig. 8A presents the *M* when the initial moisture level was varied. *MC* of 14% may be considered acceptable, whereas a higher level causes *M* over 1, even though M at 15% *MC* remains below 1 during three years but exceeds the limit during the fourth year. Moisture content over 15% is definitely unacceptable because mould growth begins in less than

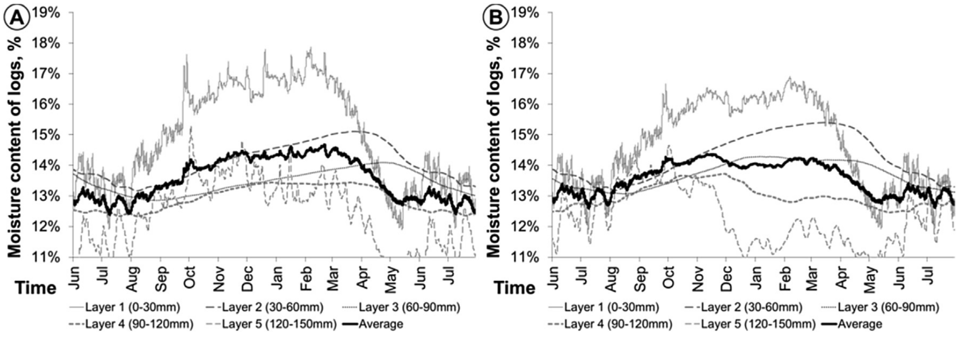


Fig. 6. Moisture content in log layers in an unheated house (A) and a continuously heated house (B).

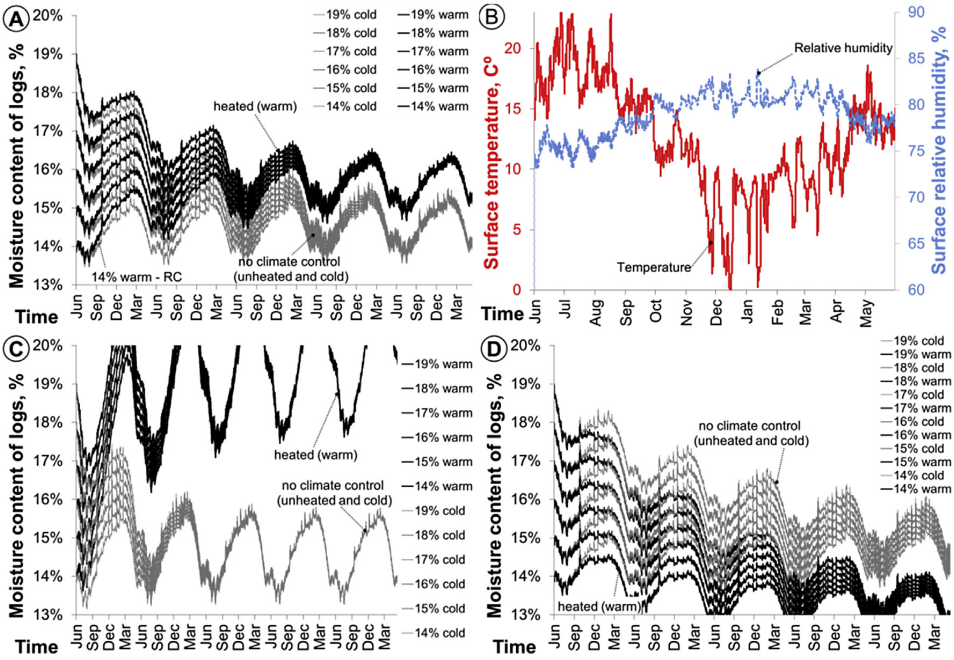


Fig. 7. Change of average *MC* in logs during a five-year period in unheated (cold) and heated (warm) houses with the reference vapour barrier – $S_d = 2$ m (A), without the vapour barrier (C), and a very vapour-tight barrier – $S_d = 100$ m (D). Temperature and *RH* on the inner surface of a log in a heated house (reference case, RC) (B).

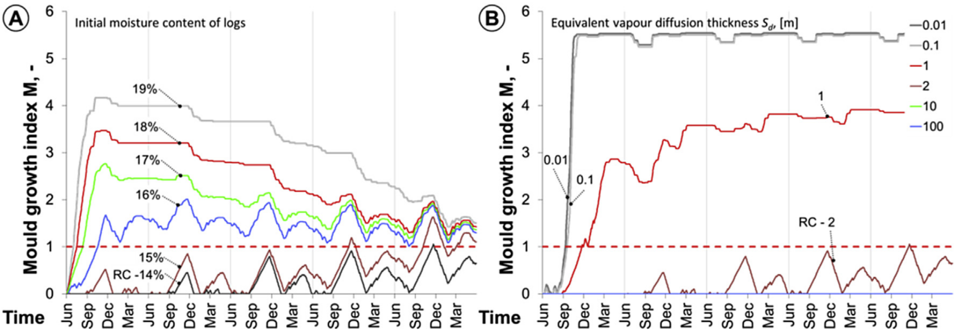


Fig. 8. Mould growth index (M) between the inner surface of a log and insulation depending on the initial moisture level of logs (A) and on the S_d of the water vapour membrane (B).

half a year, and it is not relevant when the wall has finally dried out or when mould growth stops.

Fig. 8B illustrates the need for a good vapour barrier. Barriers with small $S_d = 0.01$ m (no special vapour barrier, just gypsum board) and $S_d = 0.1$ m (range of bitumen-coated building paper) did not protect the wall construction from indoor moisture excess and heavy mould growth can be expected inside the wall. Neither did smart vapour barriers with $S_d \approx 1$ m protect against mould growth inside the wall, although growth was slower. The minimum S_d of the vapour barrier is 2 m in RC with a rather high $\Delta\nu_i$. Vapour barriers with a higher $S_d = 10$ m (similarly to laminated construction paper) and $S_d = 100$ m (range of plastic polyethylene sheeting) are well suited in these conditions.

Interior insulation thickness also has a significant effect on mould growth inside the wall (Fig. 9A). Varying the thickness of the insulation layer shows that increasing its thickness will increase M: a thickness of 50 mm may be considered as the maximum, while 75 mm is unacceptable. The effect of insulation layer thickness is higher on *M* than the thickness of a log wall: minimum thickness should be 150 mm (Fig. 9B). The thermal resistance of a mineral wool layer of 50 mm with a covering gypsum board (additional insulation with finishing layers) equals 1.3 (m^2 K)/W. The thermal resistance of a log wall (the present external wall) with a thickness of 150 mm equals 1.2 (m^2 K)/W. In order to avoid mould growth risk, the maximum thermal resistance of additional insulation with finishing layers should be almost equal to the minimum thermal resistance of the present external wall when only varying either of these parameters from RC.

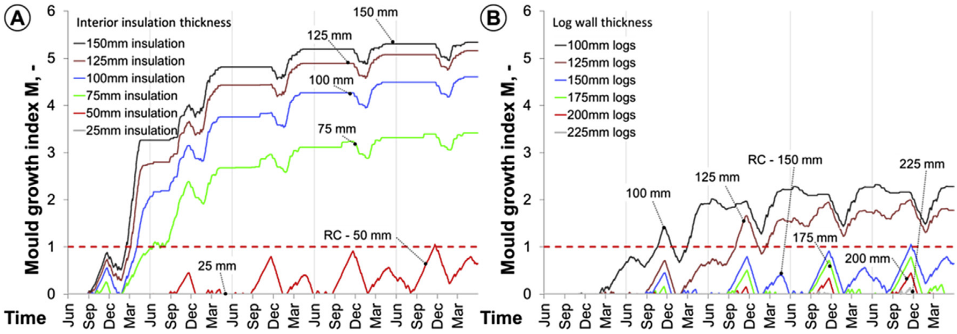
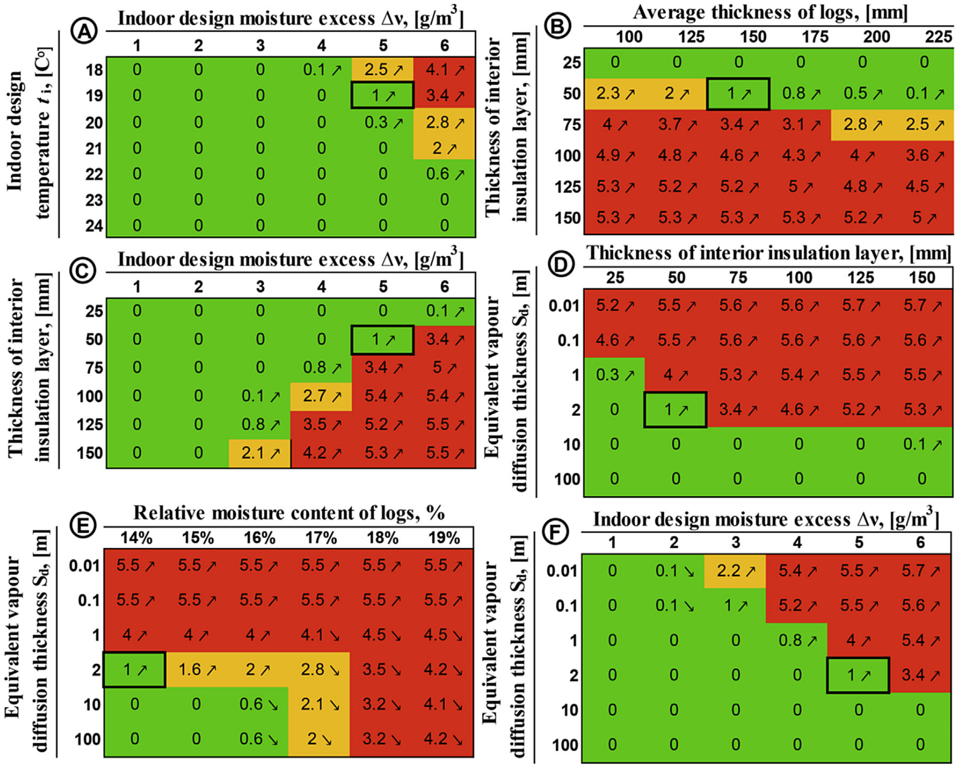


Fig. 9. Mould growth index (M) over five years on the inner surface of a log depending on interior insulation layer thickness (A) and log wall thickness (B).

3.4. Mould risk with multiple varying parameters

Previously, only one parameter of the RC was varied. To study this rather complex case, two or three parameters from the RC were varied. The following table-like figures (Figs. 10 and 11) present the maximum M on the critical surface of a wall from our five-year calculation, with the symbols ↘ or ↗ indicating the *M* trend from Year 2 to Year 5 against year 1 (lower or higher, respectively).

Generally speaking, each of the six parameters compared has a smaller or bigger effect on the temperature and RH level of a wall on the critical surface studied. Increasing the indoor humidity load or decreasing the vapour diffusion thickness of vapour barrier increases the moisture diffusion rate from indoors to outdoors through the wall, increasing the RH on the critical surface. Increasing the indoor temperature or thickness of a log wall increases the temperature and decreases the RH on the critical surface. Increasing the thickness of an additional insulation layer decreases the temperature and increases the RH on the critical



A

Indoor design temperature t_i, [C°] \ Indoor design moisture excess Δv, [g/m^3]	1	2	3	4	5	6
18	0	0	0	0.1 ↗	2.5 ↗	4.1 ↗
19	0	0	0	0	1 ↗	3.4 ↗
20	0	0	0	0	0.3 ↗	2.8 ↗
21	0	0	0	0	0	2 ↗
22	0	0	0	0	0	0.6 ↗
23	0	0	0	0	0	0
24	0	0	0	0	0	0

B

Thickness of interior insulation layer, [mm] \ Average thickness of logs, [mm]	100	125	150	175	200	225
25	0	0	0	0	0	0
50	2.3 ↗	2 ↗	1 ↗	0.8 ↗	0.5 ↗	0.1 ↗
75	4 ↗	3.7 ↗	3.4 ↗	3.1 ↗	2.8 ↗	2.5 ↗
100	4.9 ↗	4.8 ↗	4.6 ↗	4.3 ↗	4 ↗	3.6 ↗
125	5.3 ↗	5.2 ↗	5.2 ↗	5 ↗	4.8 ↗	4.5 ↗
150	5.3 ↗	5.3 ↗	5.3 ↗	5.3 ↗	5.2 ↗	5 ↗

C

Thickness of interior insulation layer, [mm] \ Indoor design moisture excess Δv, [g/m^3]	1	2	3	4	5	6
25	0	0	0	0	0	0.1 ↗
50	0	0	0	0	1 ↗	3.4 ↗
75	0	0	0	0.8 ↗	3.4 ↗	5 ↗
100	0	0	0.1 ↗	2.7 ↗	5.4 ↗	5.4 ↗
125	0	0	0.8 ↗	3.5 ↗	5.2 ↗	5.5 ↗
150	0	0	2.1 ↗	4.2 ↗	5.3 ↗	5.5 ↗

D

Equivalent vapour diffusion thickness S_d, [m] \ Thickness of interior insulation layer, [mm]	25	50	75	100	125	150
0.01	5.2 ↗	5.5 ↗	5.6 ↗	5.6 ↗	5.7 ↗	5.7 ↗
0.1	4.6 ↗	5.5 ↗	5.6 ↗	5.6 ↗	5.6 ↗	5.6 ↗
1	0.3 ↗	4 ↗	5.3 ↗	5.4 ↗	5.5 ↗	5.5 ↗
2	0	1 ↗	3.4 ↗	4.6 ↗	5.2 ↗	5.3 ↗
10	0	0	0	0	0	0.1 ↗
100	0	0	0	0	0	0

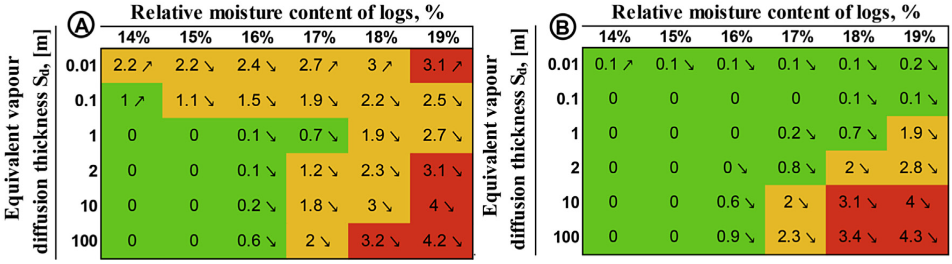
E

Equivalent vapour diffusion thickness S_d, [m] \ Relative moisture content of logs, %	14%	15%	16%	17%	18%	19%
0.01	5.5 ↗	5.5 ↗	5.5 ↗	5.5 ↗	5.5 ↗	5.5 ↗
0.1	5.5 ↗	5.5 ↗	5.5 ↗	5.5 ↗	5.5 ↗	5.5 ↗
1	4 ↗	4 ↗	4 ↗	4.1 ↘	4.5 ↘	4.5 ↘
2	1 ↗	1.6 ↗	2 ↗	2.8 ↘	3.5 ↘	4.2 ↘
10	0	0	0.6 ↘	2.1 ↘	3.2 ↘	4.1 ↘
100	0	0	0.6 ↘	2 ↘	3.2 ↘	4.2 ↘

F

Equivalent vapour diffusion thickness S_d, [m] \ Indoor design moisture excess Δv, [g/m^3]	1	2	3	4	5	6
0.01	0	0.1 ↘	2.2 ↗	5.4 ↗	5.5 ↗	5.7 ↗
0.1	0	0.1 ↘	1 ↗	5.2 ↗	5.5 ↗	5.6 ↗
1	0	0	0	0.8 ↗	4 ↗	5.4 ↗
2	0	0	0	0	1 ↗	3.4 ↗
10	0	0	0	0	0	0
100	0	0	0	0	0	0

Fig. 10. M between the inner surface of a log and insulation: indoor design temperature and Δv_i (A), thickness of an interior insulation layer and thickness of a log wall (B), Δv_i and thickness of an interior insulation layer (C), S_d of a vapour barrier and thickness of an interior insulation layer (D), S_d of a vapour barrier and relative *MC* of logs (E), S_d and indoor moisture excess (F). RC is presented in a square outlined in bold.



Ⓐ

Equivalent vapour diffusion thickness S_d, [m]	Relative moisture content of logs, %					
	14%	15%	16%	17%	18%	19%
0.01	2.2 ↗	2.2 ↘	2.4 ↘	2.7 ↗	3 ↗	3.1 ↗
0.1	1 ↗	1.1 ↘	1.5 ↘	1.9 ↘	2.2 ↘	2.5 ↘
1	0	0	0.1 ↘	0.7 ↘	1.9 ↘	2.7 ↘
2	0	0	0.1 ↘	1.2 ↘	2.3 ↘	3.1 ↘
10	0	0	0.2 ↘	1.8 ↘	3 ↘	4 ↘
100	0	0	0.6 ↘	2 ↘	3.2 ↘	4.2 ↘

Ⓑ

Equivalent vapour diffusion thickness S_d, [m]	Relative moisture content of logs, %					
	14%	15%	16%	17%	18%	19%
0.01	0.1 ↗	0.1 ↘	0.1 ↘	0.1 ↘	0.1 ↘	0.2 ↘
0.1	0	0	0	0	0.1 ↘	0.1 ↘
1	0	0	0	0.2 ↘	0.7 ↘	1.9 ↘
2	0	0	0 ↘	0.8 ↘	2 ↘	2.8 ↘
10	0	0	0.6 ↘	2 ↘	3.1 ↘	4 ↘
100	0	0	0.9 ↘	2.3 ↘	3.4 ↘	4.3 ↘

Fig. 11. M between the inner surface of a log and insulation: S_d and relative *MC* of logs at lower $\Delta v_i = 3$ g/m^3 during winter (A) or in an unheated house at $\Delta v_i = 0.5$ g/m^3 (B).

surface. Decreasing the initial moisture content of logs also decreases the moisture diffusion rate from logs to indoors, decreasing the RH on the critical surface.

Decreasing Δv_i of 1 g/m^3 has a bigger impact on avoiding mould growth risk than increasing the average indoor temperature by 1 °C (Fig. 10A). $\Delta v_i = 5$ g/m^3 should be considered as the maximum acceptable level. Decreasing the interior insulation thickness has a bigger effect than increasing the thickness of a log wall (Fig. 10B). A thin insulation layer of 25 mm may be considered safe even at a very high $\Delta v_i = 6$ g/m^3 (Fig. 10C), at $\Delta v_i = 5$ g/m^3, with a maximum insulation thickness of 50 mm, as in the *RC*. When a low $\Delta v_i = 3$ g/m^3 is guaranteed, insulation thickness may be up to 150 mm. Based on Fig. 10C, $\Delta v_i = 1$ g/m^3 has a higher effect on avoiding mould growth risk than decreasing the interior insulation thickness of 25 mm. Another possibility to use a thicker insulation layer is to install a vapour barrier with a high $S_d \geq 10$ m (Fig. 10D). When the S_d and *MC* of logs were compared (Fig. 10E), it was found that the S_d must be over 2 m or, rather, over 10 m if there is a risk of *MC* being over 14% in logs. The effect of a vapour barrier seems more important than the *MC* of logs. If $\Delta v_i = 3$ g/m^3 (Fig. 11), up to 16% of the initial *MC* of logs may be accepted and a wider range of vapour barriers may be used. Fig. 10F shows that a higher Δv_i should be coupled with a better vapour barrier (with higher equivalent diffusion thickness). There is no acceptable combination where the relative *MC* of logs is over 17% whilst a good vapour barrier (with equivalent diffusion thickness over 10 m) is used: excessive mould growth is expected in a house with a high or low Δv_i (Figs. 10E or 11A) or even in a cold house with $\Delta v_i \approx 0$ g/m^3 (Fig. 11B). Therefore, it is unacceptable to cover logs with vapour-tight layers with excessively high *MC in logs*.

3.5. Selection of a suitable vapour barrier

Selection of a suitable vapour barrier for an unheated house (cold and unused during winter) is explained in Fig. 12 by comparing the M of heated and unheated houses with two different *MC* levels in log walls (rather high *MC* of 16% or 17% was chosen for graphical reasons in order to visualise the difference). The vapour barrier in a heated house should be $S_d > 10$ m in case of the selected *MC* and at least 2 m when the relative *MC* of logs is up to 14% (Fig. 10E). In unheated houses, $S_d = 2$ m is the maximum acceptable level (Fig. 11B) when logs have *MC* above 17% at the time of insulation.

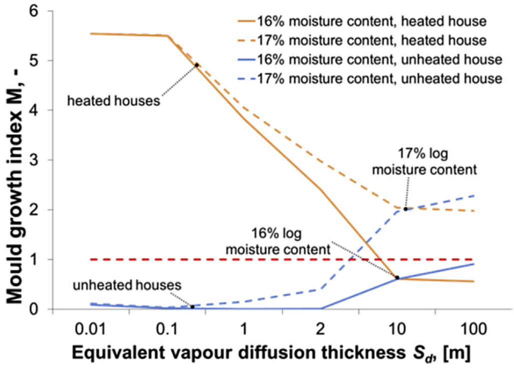


Fig. 12. Relation between the mould growth index (M) and the S_d of a vapour barrier in heated and unheated houses.

4. Discussion

Design depends on assessment and performance criteria. Viitanen [45] considers mould growth one of the most appropriate assessment criteria for the hygrothermal performance of building structures, as it is the first to indicate that moisture content in structures is too high, appearing before a structure is subjected to serious damage. Mould growth may be considered mainly a health risk for inhabitants and it may be also regarded a visual problem on surfaces. In the present study, no mould was accepted ($M < 1$) between an added insulation layer and the log wall. Vinha [47] has shown that *M* could be over 1 independently of indoor moisture loads and wall design. Under Finnish outdoor climatic conditions, *M* was between 1.7 and 3.1, calculated based on outdoor temperature and *RH*. $M > 3$ inside a structure is more critical because mould spores might be transported indoors, as demonstrated by Airaksinen [48]. According to mould growth classification, there are no spores $M < 3$ [46]. Viitanen et al. [49] propose a traffic-light classification to predict *M*: green means no risk of relevant mould growth, red represents an unacceptable risk level, and the yellow range indicates a possible risk and requires evaluation by the user. For surfaces not in direct contact with the air inside (such as the contact surface of interior insulation and the log wall considered critical in this study), it is recommended that the whole range of *M*s [49] be expanded by shifting the limits by one unit: the green light up to $M = 1$ and the yellow light up to $M = 3$. Values above 3 are marked with the red light and considered unacceptable. Similar colour coding is used here in Figs. 10 and 11. It should be noted that there is a rapid transition of *M* values from 1 to 3, as shown in Fig. 10 (only a few combinations marked with yellow); therefore, taking $M = 3$ as a criterion adds many risks but does not change the working design considerably. Accordingly, it is not advisable to design an interior insulation solution in the yellow area shown in these figures.

Based on Figs. 10 and 11, we can order the main parameters based on the effect on M, starting from the highest:

1. water vapour resistance of the vapour barrier;
2. indoor moisture load;
3. thermal transmittance of the interior insulation layer;
4. initial *MC* of logs;
5. thickness of logs, i.e. the thermal resistance of the original wall; and
6. Indoor temperature level

Installing a tight vapour barrier is more realistic than guaranteeing a low $\Delta\nu_i$ over the life cycle of a house, therefore S_d is considered more important. Logs have to dry out to a certain level anyway, and the engineer can easily choose the thermal transmittance of the insulation layer; therefore, the thermal transmittance of the insulation layer is considered more important. The effect of log thickness and indoor temperature is low; however, controlling indoor temperature during the design process is impossible. Therefore, it is assigned the lowest importance.

In this study, simple climate data, composed only of the indoor and the outdoor temperature and the *RH*, were used for the simulations. Simple climate data are considered more critical than a complete data set (with wind, sun and rain data added to the simple data set) because the effect of solar radiation increases the drying intensity that lowers *MC* in logs. Simple climate data can be explained as a wall highly sheltered from the wind and unexposed to the sun (facing north and shaded by other houses or by trees).

Heat loss through the external log wall can be reduced by about 50%, if the parameter values specified as RC are used, i.e. the thermal resistance of the added internal insulation layer equals the thermal resistance of the present external wall. Based on the results shown in Fig. 10C and D, the thickness of an additional insulation layer of mineral wool could be even higher than 100 mm, if a carefully installed tight vapour barrier with $S_d > 10$ m is used or/and the indoor moisture excess is kept below 3 g/m^3. Careful installation of the vapour barrier means that all sections of the vapour barrier are taped together with a special tape and the joints are fixed with slats, edges are sealed together with floors, ceilings and separating walls to guarantee a vapour-tight joint. The indoor moisture excess level can be decreased with an efficient continuous ventilation system. If vapour barrier and indoor moisture excess conditions are met and a calculation under specific conditions is made, then the thermal resistance of an additional insulation layer can be more than double of the thermal resistance of the present log wall. Nevertheless, increasing the thermal resistance of additional insulation also increases the risk of mould growth in the wall, if any of the conditions have not been (temporarily) met. When choosing another insulation material instead of the mineral wool used in this study and if no additional hygrothermal performance calculations are made, then it is recommended that the calculated thermal transmittance of the added insulation and the finishing layers is equal to the thermal transmittance of the log wall before the addition of the insulation. Then the thermal conditions in the wall are similar to the *RC* in this study. Reduction of air leakages through carefully installed air and vapour barrier required by interior insulation also decreases energy losses through leaky log walls more than two times. Before insulation, a 150 mm thick log wall had a thermal transmittance of $U = 0.76$ W/(m^2 K); after the addition of internal insulation of 50 mm (*RC*), it was $U = 0.38$ W/(m^2 K).

The Technical Research Centre of Finland has compared the accuracy of various *MC* meters [50]. In industry conditions (out of a laboratory), the accuracy of the resistance meters was ±2.0%–±5.0% higher than that of the capacitance meters of ±3.0–±5.0%. The uncertainty of the measuring equipment for wood *MC* depends on the stabilisation time of wood (moisture gradient in wood), measurement depth, temperature measurement accuracy, wood density, etc. The acceptable measurement range is 8%–24% for resistance meters and 5%–30% for capacitance meters. Therefore, to exclude the error of *MC* measurement devices, the measured *MC* of logs should be at least 2% lower than the values recommended in this study.

Log walls of continuously used houses have lower *MC* than similar walls in summer cottages (unheated during winter). This study shows that for a heated house, the *MC* of logs before insulating must be lower than that for unheated houses. Therefore, for an inhabitant, it is not safe to add interior insulation to an unheated house where the measured *MC* of logs is over 12% and to introduce the house into continuous use (being heated up) right after having been insulated. If interior insulation is added to an unheated house, but the use of the house remains unchanged afterwards, a higher *MC* of its log wall may be tolerated (Fig. 11B). It is necessary to take into account the measured higher *MC* when designing an interior insulation solution. A risk may also result from an unexpectedly high (either temporary or permanent) *MC* of logs, which may be caused by water leakages through external cladding or through the wall near windows, snow melting on the wall, water system leakages near the external wall, roof leakages or damp rising from the foundation (missing hydro insulation strip).

A smart vapour barrier allows moisture accumulated in logs to dry out also towards the inside of the wall, lowering mould growth risk in the wall faster. The inward drying ability is important when the initial *MC* of a log wall is higher than 14% as described in Chapter 3.5. A smart vapour barrier or another vapour barrier with $S_d \leq 2$ m is preferable in unheated houses where indoor moisture excess is lower. During the daytime in summer, exterior surfaces are often warmed to the point where the exterior is warmer than the interior, thus creating an inward vapour drive into the interior, especially in unheated houses. A smart vapour barrier also mitigates the effect of and probable damage from water leakages through roof or wall cladding, allowing moisture to dry out faster. In continuously heated houses where moisture excess is high and the *MC* of logs is $\leq 14\%$, $S_d \geq 2$ m is preferred because an outward vapour drive dominates all year round.

The *RC* was considered suitable if $M \leq 1$ during a five-year period. The safety margin of the calculations consists in the following:

- In our calculation, the critical moisture test reference year for mould growth was used. Although the *M* value showed an increasing trend over the course of five years, there is almost no possibility of five consecutive years with the same critical climatic conditions.
- A design curve of moisture excess (90% fractile) was used in our deterministic analysis; accordingly, moisture flow through the wall was above average. In practice, the difference between weekly maximums and the average moisture excess measured is about a half of that [39]. For a stochastic analysis, an average moisture excess with certain variations [33] should be addressed by future research.
- A north wall not exposed to any solar radiation was analysed, and temperature and *RH* were the only boundary conditions for the external climate. For orientations in other directions, the hygrothermal performance of an internally insulated log wall is better due to solar radiation. It should be taken into account that if a wall is wet, solar radiation may cause inward drying and considerable moisture flow into interior insulation.

5. Conclusions

A wooden log wall was analysed by varying its indoor humidity load, average indoor temperature, the thickness of the log wall and an additional insulation layer, the initial moisture content of logs and the vapour diffusion thickness of the vapour barrier using a previously validated hygrothermal calculation model. It is important to note that the hygrothermal calculation model was validated in cold climatic conditions, and therefore the results of simulations presented in this paper apply to a wall in a cold climate. Mould growth risk for each combination was described and based on these results, and the combinations were considered as hydrothermally safe (no mould growth in the wall) or non-functioning solutions (M value over 1).

The main conditions and parameters required in order to avoid mould growth risk in an interiorly insulated wall structure are as follows:

- The water vapour resistance of a vapour barrier depends on the use of the house and its indoor humidity load; therefore, the choice of an appropriate material should be based on the values indicated in this study, or else calculations are required in each individual case.
- The maximum thermal resistance of an additional internal insulation layer with finishing layers should not be above the thermal resistance of the log wall before the addition of the insulation. If an improved vapour barrier with efficient sealing methods is used, lower indoor moisture excess is guaranteed with ventilation, hygrothermal calculation for a specific case is made and increased risk of mould in the wall can be tolerated, then the thermal resistance of an additional internal insulation layer can be more than double of the thermal resistance of the present log wall.
- Before insulation, a log wall has to be as dry as possible, i.e. at the measured initial average moisture level of $MC \leq 12\%$ if mineral wool with a vapour-tight barrier is used.
- It is necessary to ensure the airtightness of a wall and especially the vapour barrier covering the interior insulation; any penetrations (electric installations, etc.) are unacceptable.
- It is necessary to guarantee the required ventilation and heating in a house by means of reliable technology.

Changing the water vapour resistance of a vapour barrier or indoor moisture load were found to have the biggest effect on the mould growth index, whereas the average thickness of logs and indoor temperature levels had a small effect on the mould growth index. This means that the choice of the right vapour barrier and its careful installation, together with low (controlled) indoor moisture loads, are the primary conditions to avoid mould growth in an interiorly insulated log wall.

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PAPER IV

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Comparison of Mineral Wool, Cellulose and Reed Mat for Interior Thermal Insulation of Log Walls

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Abstract: Interior thermal insulation in cold climate is risky from a hygrothermal point of view. Designers and customers are looking for solutions that provide moisture safe design. In this study three insulation materials (cellulose fibre, reed mat and mineral wool) were compared and different structural and indoor climate parameters were varied to find out limitations for log wall insulation. A calculation model was validated based on our field measurements. In general, our results showed that logs must have a measured moisture content of ≤ 14%, an interior insulation layer of ≤ 50 mm thickness and a mechanical balanced ventilation system with heat recovery must be provided to ensure moisture safety. Airtightness of the log wall and the vapour barrier are to be ensured. As the reed mat with clay plaster allowed the structure to dry on both sides and the material has higher thermal conductivity, slightly higher initial moisture content and thickness of insulation are acceptable. Before covering with an air or a vapour barrier, cellulose fibre installed by a wet method has to be dried for at least one week. Our results can be used in the design of interior thermal insulation for rural houses in the northern cold climate.

Key words: Hygrothermal performance, interior thermal insulation, rural houses, moisture safety, mineral wool, cellulose fibre, reed mat.

1. Introduction

Log houses have a long history and they represent a variety of building techniques employed in Estonia and in other Nordic countries. Besides the high air leakage rate of old log houses [1], the thermal transmittance of a traditional log wall built about a century ago is too high in the background of current energy prices and national building regulations in many countries. Therefore, the requirements for energy-efficiency, thermal comfort, and function in a log house are different and higher than a century ago.

Many studies have analysed the possibilities and limitations to use the interior thermal insulation for improving the thermal resistance of old external walls [2-14, 15]. The focus has been on stone walls [2-11], which are more widespread in cities. Studies of the interior insulation of log walls with a calculation model either theoretical or validated with real measurement data are rare. Ojanen [12] studied the interior insulation with a theoretical model and assumed that the log wall was completely airtight, but vertical air channels between the log and the insulation layer were suggested to reduce the moisture level. Arumägi & Kalamees [13] and Alev et al. [14] measured old log walls with a high leakage rate and validated the respective calculation model by modifying the selected material properties of the wall. They found that the log wall is not completely airtight and to validate the simulation model, the air change through the log wall was added. Other differences between mentioned studies include the type and usage of a house, used insulation materials, hygrothermal loads etc.

The main wall and insulation materials can have a wide scale of properties (initial moisture content, thickness, etc.) and the indoor climate in each house can be different. In addition to the present situation in old houses analysed in Refs. [13, 14], the designers and builders of new houses need to know the limitations and risks concerning the hygrothermal performance of interior insulation. Interior insulation is more complex and not as hygrothermally safe as widely used exterior insulation [10]. Therefore, the designer needs knowledge of the maximum thickness of the insulation layer and a list of other materials required and the builder needs knowledge of an appropriate building technology and a time-scale for building a new house. Previous studies lack such information in different combinations.

The interior insulation technique is mainly needed in old houses with massive walls made from stones or wooden logs. This study concentrates on log walls, being less studied compared to different stone walls. Colder climate causes even higher condensation or mould growth risk in external wall construction compared to warmer climatic conditions where most of the measurements or calculations were made [2-4, 6-11]. Homeowners prefer cheap and/or natural insulation materials used in this study over the more expensive and less common materials like capillary active insulation systems [2, 3, 5, 8, 9], vacuum insulation panels [11] or special renders [2]. In addition, easy installation of insulation is important factor when choosing materials for renovation solution. Therefore the capillary active materials may be not suitable for interior insulation of log walls.

The current study was carried out in a specially designed and constructed test house with a log wall interiorly insulated with three different insulation materials. The aim was to study the influence of built-in moisture on the hygrothermal performance and to find out the indoor climate and structural parameters/limitations for hygrothermally safe insulation solutions. The limitations were investigated by varying selected parameters in calculation model, which was previously validated with measured data.

2. Materials and Methods

2.1 Compared Wall Sections

The insulated wall was made with half round logs of an average thickness of 270 mm. The wall was insulated from the interior side with mineral wool, cellulose fibre (both covered with a water vapour barrier and a gypsum board) and a reed mat with clay plaster (Figs. 1 and 2). The interiorly insulated wall faced west, shaded with wooden cladding, a ventilated air gap of 250 mm was provided between the boards and the log wall to protect the wall and sensors from direct sun radiation (Fig. 1a).

2.2 Calculations

The WufiPro5.1 (WUFI) software was selected for the hygrothermal performance analysis. WUFI is used to solve the transient coupled one-dimensional heat and moisture transport in a multi-layer building component. Several studies have used WUFI calculation results against field measurements [16, 17]. WUFI offers temperature and relative humidity values among other parameters at specified depths/layers of construction. For the numerical solution, WUFI uses the finite volume technique for the spatial discretisation of the moisture and energy transport equations (Eqs. 1 and 2) and uses a fully implicit scheme for the discretisation in time [18].

Moisture transfer:

$$\frac{\partial w}{\partial \varphi} \cdot \frac{\partial \varphi}{\partial t} = \nabla \cdot \left(D_{\varphi} \nabla \varphi + \delta_{p} \nabla (\varphi \cdot p_{sat}) \right) \quad (1)$$

Energy transfer:

$$\frac{\partial H}{\partial T} \cdot \frac{\partial T}{\partial t} = \nabla \cdot (\lambda \cdot \nabla T) + h_{v} \nabla \cdot \left(\delta_{p} \nabla (\varphi \cdot p_{sat}) \right) \quad (2)$$

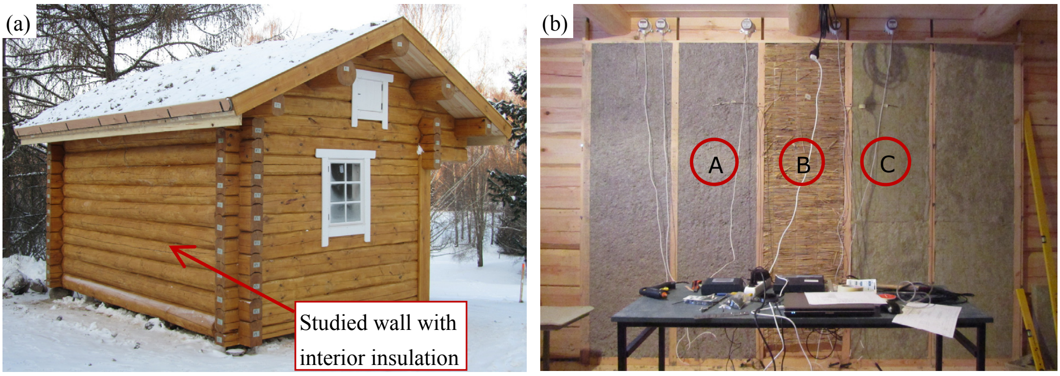

Fig. 1 View to the interiorly insulated wall from outside (a) and from inside before covering with finishing layer (b).

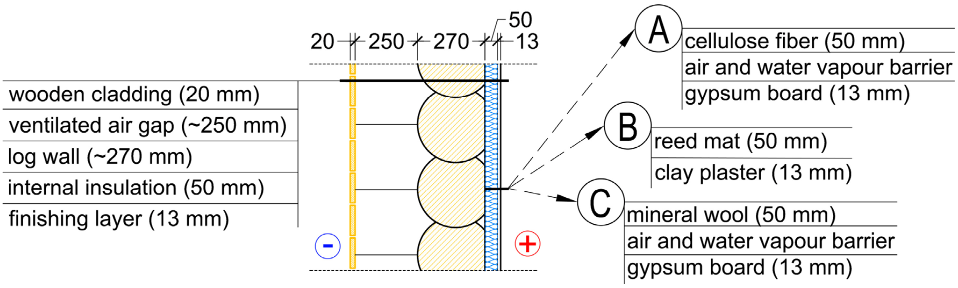

Fig. 2 Section of the interiorly insulated wall.

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).

The calculation model in WUFI was composed and validated on the basis of the field measurement data [15]. Table 1 shows the properties of the materials used in the calculations [15]. The critical surface in the wall from the moisture-safety point of view was the inner surface of the log wall directly in contact with the insulation layer.

Estonian moisture test reference year [19] was used for outdoor climate after validating the model with the measured outdoor climate.

The moisture content in a log wall is floating according to the season. When the logs are exposed to outdoor climate from both sides, the calculated moisture content of the surface layer (30 mm thick) was 13% during the summer period (hot season) and 17% during the winter period (cold season). If the measured moisture content of kiln-dried logs is 22% [15] and

Table 1 Main properties of the materials used in the simulation.

	Wooden log	Mineral wool	Cellulose fibre	Reed mat	Vapor barrier	Clay mortar	Gypsum board
Bulk density ρ, kg/m^3	390	60	60	136	425	1568	850
Porosity f, m^3/m^3	0.75	0.95	0.95	0.9	-	0.41	0.65
Specific heat capacity c, J/(kg·K)	1600	850	2000	2000	2300	488	850
Thermal conductivity λ, W/(m·K)	0.12	0.04	0.037	0.075	-	0.48	0.2
Vapour diffusion resistance factor μ, -	108	1.3	1.5	2.0	37500	20	8.3
Built-in moisture w, kg/m^3	66	0.8	8.0	6.0	0	100	2.0

average moisture content of dried logs in heated houses (older than 5 years) is up to 12%, then the initial moisture content of 17% represents half-dried logs. Therefore, in our calculations, the initial moisture content of 17% was selected for the log wall. Our calculation period selected started in June because by that time the logs had dried and had the lowest moisture content. In addition, it is a private homeowners' active building and renovation period.

To find out a hygrothermally safe solution, multiple parameters were varied:

For indoor climate, four different indoor humidity loads were used: +4/1 g/m^3 (low humidity load in dwellings); +5/1.5 g/m^3 and +6/2 g/m^3 (high humidity load in dwellings) at outdoor temperatures below +5 °C/above +20 °C.

The thickness of the log wall was varied from 100 mm to 200 mm with a 25 mm step.

The thickness of the interior insulation layer was varied from 50 mm to 150 mm.

The initial moisture content of logs varied from 14% to 26%.

Different water vapour barrier materials were used on the mineral wool and cellulose fibre insulation layer: polyethylene foil (PE) (S_d = 18 m); smart vapour retarder membrane (SVRM) (variable S_d = 0.25-25 m); laminated paper (LP) (S_d = 1 m) and without the water vapour barrier layer.

To compare different solutions, the reference case was determined: moisture excess 4/1.5 g/m^3; log wall with a thickness of 200mm and moisture content of 17% at the building period; thickness of the insulation layer of 50 mm; SVRM (reed mat without an additional water vapour barrier) and the finishing layer was always a gypsum board on top of mineral wool and cellulose fibre insulation and clay plaster on top of reed mat. The air and vapour barrier and plaster provided the airtightness of the wall.

2.3 Assessment of Hygrothermal Performance

The moisture safety was assessed based on the risk of mould growth between the log and the interior insulation. The temperature and relative humidity hourly output from the simulations was post processed and the mould growth index was calculated for the critical surface in the wall based on the Hukka and Viitanen [20] and the Ojanen [21] calculation model. The mould growth index represents the possible level of mould growth on a wooden surface according to the following scale [20]:

0-no growth;

1-some growth detected only with microscopy;

2-moderate growth detected with microscopy (coverage more than 10%);

3-some growth detected visually;

4-visually detected coverage more than 10%;

5-visually detected coverage more than 50%;

6-visually detected coverage 100%.

Mould growth index below 1 (no growth) was considered moisture-safe and these structure and indoor climate combinations were suggested.

The uncertainty of measuring equipment for wood moisture content is usually ≈ 2%. Therefore, the *measured* moisture content of the logs is 2% lower in the results than the values used in the calculation model and shown on the mould growth index graphs.

3. Results

Different combinations of the described parameters were calculated with the simulation software WUFI. Mould growth index in the critical point in the wall is presented in the figures below and mould growth index level 1 is marked with a grey line below which safe values occur (combinations).

The initial moisture of a log can be the dominant moisture source for an interiorly insulated log wall, in particular when the assembly is equipped with a vapour barrier. Fig. 3 presents the mould growth index for all three insulation materials when the initial moisture level was varied (the other parameter according to the reference wall). The wall with reed mat insulation is able to dry out to both sides (indoors and outdoors), the insulation material has some moisture storage properties, and it is not covered with the water vapour tight layer from the inner side. Therefore, this wall has the highest acceptable initial moisture content of the log. As the cellulose fibre is installed by a wet spray method, it brings additional moisture to the assembly. Therefore, the cellulose fibre insulation layer needs to stay open at least for a week before covering with a water vapour barrier and a gypsum board. After covering that assembly with a water vapour barrier, the constructional moisture can dry out only to outdoors. This assembly accepts a measured initial moisture content of up to 15% for a log wall when the insulation layer has dried at least for a week in a heated and continuously ventilated room before covering. When the insulation is covered with a water vapour barrier just after installation or the room is unheated or not continuously ventilated, the acceptable measured initial moisture level is 12%. The acceptable measured moisture content of logs with mineral wool insulation is up to 14%, even though the insulation itself is dry, the insulation has about 10 times lower moisture storage capability than cellulose fibre.

High moisture content is especially critical when the assembly is equipped with a vapour barrier on the inner surface of insulation. Fig. 4 shows walls with cellulose insulation and mineral wool with different resistances of the vapour barrier and the calculated initial moisture content of 17% in logs. Membranes with high water vapour resistance (PE and SVRM) resulted in high mould growth risk when the covered insulation was wet cellulose fibre. In both cases LP resulted in the lowest mould growth levels. The solution without vapour barrier was not on the safe side

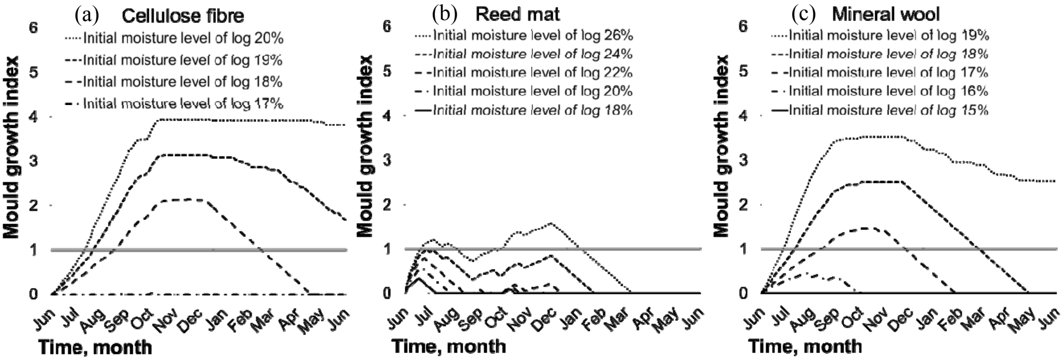

Fig. 3 Mould growth index on inner surface of a log in contact with cellulose fibre (a), reed mat (b) and mineral wool (c) depending on the initial moisture level of logs.

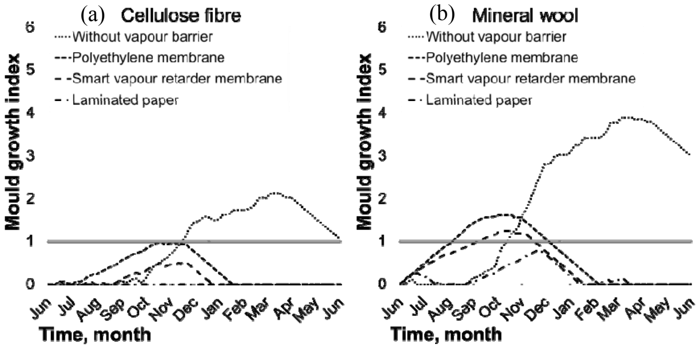

Fig. 4 The dependency of water vapour resistance of a vapour barrier on the mould growth index on the inner surface of the log in contact with cellulose fibre (a) and mineral wool (b).

in both cases, although the mould growth level was lower with cellulose fibre probably because of higher moisture buffering capacity in cellulose fibre. When both the log wall and the insulation layer have dried out, it is safe to cover them with either PE or SVRM (Fig. 4b).

The thickness of a log influences the hygrothermal performance of a wall by different constructional moisture of the log and thermal and vapour resistance on the exterior side of insulation. Nevertheless, the impact of the thickness of the log on the hygrothermal performance of an interiorly insulated log wall is rather small (Fig. 5). A general understanding that a thicker wall is hygrothermally safer is valid only in the case of reed mat insulation. The inwards drying is limited with the interior vapour barrier (walls with cellulose fibre and mineral wool). A thicker wall has higher thermal resistance and therefore the interior surface temperature increases and the RH decreases. The increase of the interior surface RH caused by a larger amount of drying water in a thicker log will dominate the small RH decrease from the higher thermal resistance of the thicker wall. As the measured moisture content of logs of 15% (reference wall) is too high for cellulose fibre, the mould growth index of both a 100 mm and a 200 mm thick wall is high. In contrast, when the wall is insulated with mineral wool, the mould growth index is lower than 1 in case of both thicknesses.

Varying the thickness of the insulation layer (Fig. 6) shows that increasing the thickness will increase the mould growth index. The impact of the insulation layer thickness is higher on the mould growth index than the thickness of the log wall. Even the 50 mm thick layer of cellulose fibre has the mould growth index higher than one, but the curve shape is similar to mineral wool insulation. It is safe to use a 70 mm thick reed mat, a 50 mm thick mineral wool and a 50mm thick cellulose fibre insulation layer if the cellulose fibre is dried out before covering with an optimal water vapour barrier (laminated paper). The results are sensitive to the water vapour resistance of the selected vapour barrier (Fig. 4). Insulation thicknesses above the mentioned values can be possible only in certain conditions (dry thick log walls, low indoor humidity load, water vapour barrier with proper vapour resistance (calculated)).

When the log wall is covered by exterior boarding and protected by driving rain, the dominant humidity loads are from indoors and the log by diffusion. Varying the indoor humidity load (Fig. 7) showed that the highest acceptable indoor design moisture excess during winter (Δv) with reed mat insulation is 5 g/m^3. The design moisture excess of 4 g/m^3 is acceptable with mineral wool and cellulose fibre (after drying out) interior insulation. The design indoor moisture excess is approximately two times higher than an average value [22].

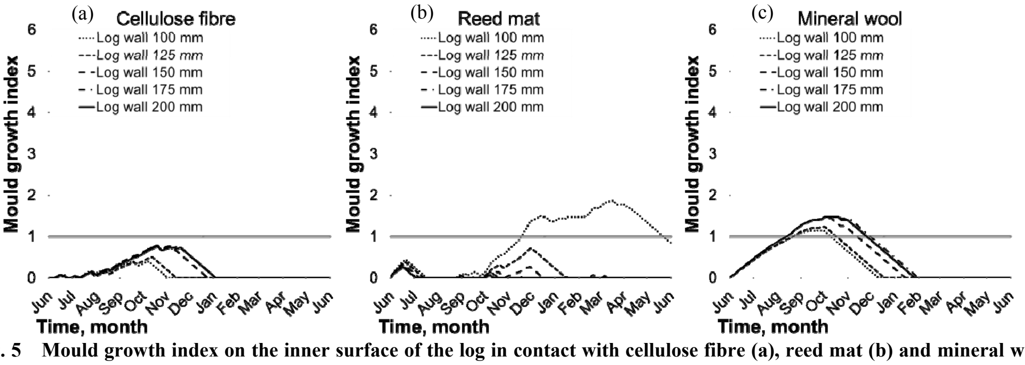

Fig. 5 Mould growth index on the inner surface of the log in contact with cellulose fibre (a), reed mat (b) and mineral wool (c) depending on the log wall.

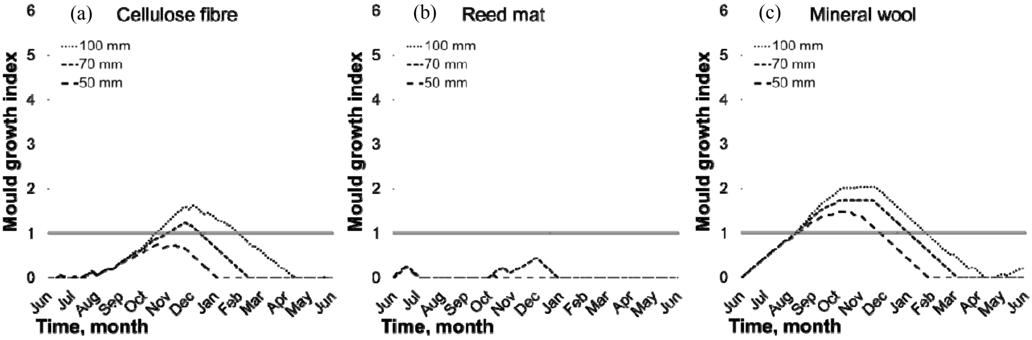

Fig. 6 Mould growth index on the inner surface of the log in contact with cellulose fibre (a), reed mat (b) and mineral wool (c) depending on the interior insulation layer.

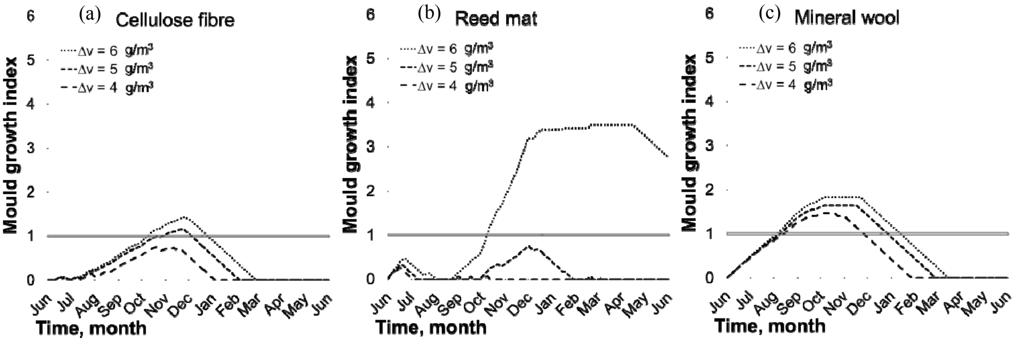

Fig. 7 Mould growth index on the inner surface of the log in contact with cellulose fibre (a), reed mat (b) and mineral wool (c) depending on the indoor humidity load.

4. Discussion

The study shows the importance of planning the building process. Logs with high moisture content must have time to dry to a safe moisture level. When the measured moisture content of new kiln-dried logs is 22% [15], the drying to a safe moisture content (measured value up to 14%) takes about a year in a heated (≈ 20 °C) and continuously ventilated (low humidity load) house. When the indoor conditions are not met, the moisture content of logs has to be measured until the specified value is reached. Also, insulation materials with a wet installation technology must have enough time to dry out before covering with a water vapour tight layer. In the current study, cellulose fibre needed at least one week to dry in a heated (≈ 20 °C) and continuously ventilated (low humidity load) room to an almost stable moisture content of 8 kg/m^3. The mentioned stable moisture content of cellulose fibre cannot be reached in an unheated house or with high humidity loads, the measured moisture content of logs has to be ≤ 12%.

Interior thermal insulation is acceptable only at low indoor humidity loads (average moisture excess values during the cold period +2 g/m^3). Higher indoor humidity loads have to be avoided with continuous usage of a decent (silent, energy efficient, no draft etc.) balanced mechanical ventilation system with heat recovery. Climate control is also important during the construction process to dry out built-in moisture from the materials. Usually the ventilation system is not used during the construction period because of the high dust content in the air. Therefore, an alternative system (ventilation or drying) has to be used to guarantee the continuous high air change rate in the rooms. When the step-by-step building process is acceptable by the inhabitants, it is good to use the house for a couple of years before adding the interior insulation layer.

In this study a simplified test reference year climate data was used, including only outdoor temperature and RH values and excluding sun radiation, rain and wind data. Simplified outdoor data showed higher RH values in the wall because of the good drying potential of sun radiation and wind; the added humidity load on the facades caused by driving rain was minimal due to long eaves of traditional private wooden houses. Simplified climate can be interpreted as a house shaded by trees or buildings nearby (minimized sun, wind and rain influence). In addition, the north façade, which is exposed to minimal direct sunlight, has been the most critical.

Even though several combinations have been calculated and presented in this article, every particular interior insulation case should be calculated with dynamic heat air and moisture software to ensure the moisture safety of the wall. The results should be compared to the results in this article or referenced articles to avoid major errors.

In current study the parameters for a one-dimensional wall were calculated, but for corner areas and thermal bridges, these solutions may not be applicable due to lower interior surface temperatures of the wall and probable leakage places near the corners. These areas have to be designed and built with special care to avoid mould growth in these areas. Additional research to determine parameters for these areas is needed. In this study the most critical conditions were chosen: test reference year considering outdoor climate with the highest mould growth risk in combination with a more critical simplified version of climate data; high moisture content of logs and a strict approach that excludes mould growth in each combination.

5. Conclusions

Based on the validated hygrothermal model in software WUFI, three different interior insulation materials were analysed. The initial moisture level in the log wall, the thickness of the logs and the insulation layer, the vapour barrier and the indoor humidity load were varied in the model. Hygrothermal performance of cellulose fibre and mineral wool interior insulation systems performed similarly. The main difference was that cellulose fibre was installed by a wet method and the moisture had to dry out before covering it with a vapour barrier. Reed mat interior insulation performed differently, allowing the log wall dry out also to the interior side and also the thermal conductivity of reed was lower than that of mineral wool or cellulose fibre.

The conditions and parameters needed for a hygrothermally safe interiorly insulated wall construction are as follows:

Balanced mechanical ventilation with heat recovery and a heating system is required. Average humidity loads higher than +2 g/m^3 during the cold period when cellulose fibre or mineral wool insulation is used and 2.5 g/m^3 when reed mat is used during the heating period should be avoided.

Cellulose fibre insulation has to dry at least for one week in a heated (≈ 20 °C) and continuously ventilated (low humidity load) room after installing and before covering it with a water vapour barrier.

Log wall has to be as dry as possible before insulation works: measured initial moisture level has to be ≤ 14% when mineral wool with a vapour barrier is used; ≤ 15% when cellulose fibre is installed by a wet method (previous condition is essential; ≤ 12 if previous condition is not met) and ≤ 22% when reed mat with clay plaster is used.

The maximum thickness of an added insulation layer can be 50 mm (cellulose fibre or mineral wool) and 70 mm with a reed mat.

The water vapour resistance of a vapour barrier depends on the usage of the house and the indoor humidity load, therefore a proper material should be chosen based on the calculation made for every particular case.

The airtightness of the wall and especially the vapour barrier covering the interior insulation must be ensured, penetrations (electric outlets, etc.) are not allowed.

The airtightness of the log wall should be ensured by precise log cutting technologies and proved by sealing ribbons between the logs.

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PAPER V

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Renovation alternatives to improve energy performance of historic rural houses in the Baltic Sea region

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ABSTRACT

This paper analyses renovation alternatives to improve energy performance of historic rural houses in three countries (Estonia, Finland, Sweden) in the Baltic Sea region (cold climate). The study was conducted by a combination of field measurements and simulations. Indoor climate, typical houses and structures as well as the current condition and need for renovation were determined by field measurements. Based on field measurements, indoor climate and energy simulation models were validated and used to calculate energy use for different renovation measures. Energy renovation packages were calculated for different scenarios (minimal influence on the appearance of the house, improvement of thermal comfort, improvement of building service systems) for different energy saving levels. The analysis showed that the improvement of building service systems and the energy source holds the largest energy saving potential. The building envelope of old rural houses needs improvement also due to high thermal transmittance and air leakage. The insulation of the external wall has the largest single energy saving potential of the building's envelope. The results show how energy savings depend on energy saving targets, typology of the building, thermal transmittance of original structures, and building service systems.

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1. Introduction

With the recast of Energy Performance of Buildings Directive (EPBD) [1] Europe has adopted an ambitious vision for the energy performance of its buildings. Lechtenböhme and Schüring [2] clearly showed that the improvement of the building shell of residential buildings offers a huge potential for energy savings which amounts to an annual 90 Mtoe by 2030 for the EU27. Over two thirds of this enormous potential is located in existing buildings. Therefore, in addition to new buildings, also existing buildings undergoing extensive renovations, will have to meet 'very high energy performance' standards by 2021.

Energy-renovation of buildings is a multi-criteria approach, where the cost of refurbishment, annual fuel economy after refurbishment, tentative pay-back time, harmfulness to health of the materials used, aesthetics, maintenance properties, functionality, comfort, sound insulation and longevity, etc., should be taken into account [3]. The cost-effectiveness, energy performance and environmental impact are typically used in the optimization of renovation solutions [4], [5]. Zavadskas and Antucheviciene [6] combined the economic benefits of the regeneration of buildings with the environmental potential as well as social interest. Optimisation can be done before or after setting the levels for energy performance requirements. Cost-effectiveness [7] can be considered when setting the levels for energy performance requirements [8] or designing of new buildings [9].

In addition to many quantitative values, optimisation may include also qualitative measures. Preserving environmental and historic values of buildings is one of the important considerations in all energy-renovation projects. Environmentally or historically valuable buildings may not follow the strict requirements on energy performance. As the overall number of historically valuable buildings is generally small, lower requirements for energy performance for valuable buildings do not destroy the ambitious vision for a reduction in the overall energy use of buildings. Therefore, energy performance requirements may be set according to realistic energy performance measures that do not destroy the historic value of buildings. Due to this, it is necessary to calculate energy performance for different renovation measures.

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Fig. 1. Example houses from Estonia (left), Finland (middle) and Sweden (right).

Many studies [10,11] have analysed the improvement of energy performance of historic buildings in towns. Much less information exists about energy-renovation of traditional rural houses. In their recent research, Bjarløv and Vladykova [12] have demonstrated practical ways of reducing thermal bridges significantly, increasing air tightness, upgrading insulation and adding mechanical ventilation to approximately half of the housing stock without significantly changing the architectural expression or having to relocate the occupants during the renovation for standard family detached and semi-detached wooden houses in arctic Greenland. Todorović [13] stated that it is impossible to reach sustainability without harmonious interdisciplinary interaction, without a balance between the physical and the spiritual, science and art, technology development and cultural and other human value improvements without an ethic of sustainability. Therefore, it is important to consider historic and milieu values in the improvement of the energy performance of traditional rural houses.

Even if there are no official requirements for the energy performance of historic buildings, owners and inhabitants of buildings wish solutions to be proposed for improvements of energy performance due to high maintenance costs. Therefore, a multi-criteria approach is a useful tool also in this area. The optimisation of renovation depends on a variety of aspects, such as the initial levels and the final purpose of the energy performance changes, indoor climate, historic and social values, the necessity for renovation from structural, building physical, indoor environmental building service related features. For decision making both are important: improvement as a percentage from initial conditions as well the final level. Whether or not the need for renovation is high, energy related measures are more effective. Therefore, energy performance should be analysed from the state of “as built” up to different renovation measures.

Current paper analyses renovation alternatives to improve energy performance of historic rural houses in three states (Estonia, Finland, Sweden) in the Baltic Sea region (cold climate).

2. Methods

The study was done by a combination of field measurements and simulations. Indoor climate, typical houses and structures, as well the current condition and necessity for renovation were determined by field measurements. Based on field measurements, indoor climate and energy simulation models were validated and used for the calculation of the use of energy for different renovation measures.

2.1. Studied houses

There were 24 historic rural houses in Estonia (EST), 20 houses in Finland (FIN), and 23 houses in Sweden (SWE) under investigation. In each of the three regions, the houses described in Chapters 2.1.1–2.1.3 were considered of the same type. From the studied houses, three example houses were selected, one house from each country (see Fig. 1, Table 1) representing a typical rural house and renovation needs in the Baltic Sea region. The function and technical information of the studied houses are summarised in the next three paragraphs below and in Table 1. The technical condition and need for renovation are analysed (Section 2.2.1).

2.1.1. Estonia

In Estonia the predominant historic farmhouse is a barn-dwelling. The poly-functional barn-dwelling served both, as a living and husbandry building. It consists of three main parts end to end: a kiln-room, a threshing room and bedrooms (Fig. 2). The kiln-room served as a living and working room all year round, although in autumn grain was dried there. Over time improvements have been made to enhance houses and better adapt them to people’s needs [16]. At the turn of the 18th to19th century, the need to build chimneys in dwellings in order to get rid of smoke was considered to be most urgent. The barn-dwelling was far from comfortable and cosy for people. Even though the barn-dwelling adequately corresponded to the general needs of life of the peasants then, it included many shortcomings from a modern person’s point of view.

Nowadays the kiln-room is mostly used as a kitchen, but also as a living room or storage. Depending on the use of the current house, the threshing room is used as a garage or storage. The threshing room is usually unheated because the external walls are typically made of natural stone with a thickness of 0.5–0.7 m. The external walls of the kiln-room and bedrooms are made of wooden logs with a thickness of 0.12–0.20 m. The houses were mainly heated with wood heated ovens. Typically, there was only passive stack ventilation and window airing. Domestic hot water was originally heated by kitchen ranges and nowadays mostly by electricity.

2.1.2. Finland

In Finland, the most common historic house type is a log house which is used only for living purposes. Eighty percent of the studied Finnish houses were that type log houses. Even though they were built during the long period of 1700–1940, the basic wall structure of different buildings is similar. The cladding is made of wooden board. Traditional roof structure is shingle and it can still be found under the tile or tin roof. Tin is the most common roof material in the studied buildings. The most frequent floor structure is a plank floor with an outdoor-ventilated crawl space. The floor structures have been originally constructed with different thermal insulation layers of sand, moss or sawdust and birch bark. They have undergone changes during renovations. After renovation, original insulation has been replaced in many of the studied houses with wood fiber board or other insulation materials. In Finland, traditional windows have two glass panes in wooden frames. Windows have already been renovated in several studied houses and, for example, new triple glazed windows had been installed in one house. Doors are traditional wooden doors without any thermal insulation in all the studied houses.

Traditionally, historic houses were heated with wood heated ovens in Finland. Because of this, all the studied houses are

Table 1
Characterisation of studied houses and an example houses “as built”.

	Estonia		Finland		Sweden	
	Average (range)	Example house	Average (range)	Example house	Average (range)	Example house
Building’s size and shape						
Heated floor area, m^2	80 (40–180)	75	139 (57–250)	154	180 (76–339)	244
Area of building envelope, m^2	267 (137–580)	272	362 (166–671)	455	412 (182–742)	490
Percentage of window from total facade area, %	7.5 (2.4–14.9)	4.3	9.7 (1.8–26.8)	9.6	10.6 (7.2–17.8)	13
Thermal transmittance of building envelope U, W/(m^2 K)						
External walls	0.36–0.85	0.55	0.28−−1.3	0.52	1.5–2.0	1.82
Roof/attic floor	0.22–1.7	0.69	0.16–0.45	0.38	0.10–0.78	0.33
Based floor	0.5–2.4	1.6	0.26–0.7	0.38	0.68–1.3	0.68
Windows	2.7–2.9	2.9	2.7–2.9	2.8	2.9–3.5	2.9
Air leakage rate q_{50}, $m^3/(h\,m^2)$	15.8 (3.9–35)	15.9	12.2 (5.2–26)	11.5	17.4 (12–33)	14.8

Outdoor climate	Estonian TRY [14]	Finnish TRY [15]	Gotland, year 2000
Design temperature for heating sizing, °C	−21 °C	−26 °C	−10 °C
Annual heating degree days at t_i 17 °C	4160 °C·d	3952 °C·d	3127 °C·d

equipped with them, although auxiliary electric heating was installed in several houses. Modern heating systems in renovated historic houses are quite diverse because, for example, ground source heat pump was installed in one of the houses and two houses were even heated with district heating.

2.1.3. *Sweden*

Swedish houses were selected from Gotland, where the houses are usually built with dry wall technique (limestone or sandstone stones stacked on top of each other, kept in place with smaller balance stones and without mortar). The façades are plastered and painted with lime wash in different colours. The most common roof covering is tiles. There are different constructions of trusses and roof coverings. The older kind of tile covering is without roof boards, you can see the tiles from the attic. The most common roof shapes are gable and mansard roofs. Traditionally, the space underneath the roof was not used for living, but for storage. The windows are either single or double glazed. In some of the studied houses the owners use removable inner window frames which are installed during the whole heating season. Doors are made of wood and are more or less decorated. Doors from the late part of the 19th century and later often have a glazed part.

All the studied houses have different kinds of fire places. The oldest kinds of fireplaces are the open ones used for cooking, often with a baking oven. The tiled stoves started to be installed in the 19th century. In some places cast iron stoves were added to the tiled stove in order to take advantage of the quick radiant heat. Today the fire places are not used as the main source of heat. In the 1960s, many oil fired boilers with radiator heating systems were added. In the 1970s, electric radiators were installed if only fireplaces heated the building at that time. Since the 1990s, many oil fired boilers have been converted to burning firewood, wood pellets and wood chips, or replaced with new boilers burning bio fuel. Though, some oil fired boilers are still left. Direct electric heating is used if there is no water borne system.

2.2. *Renovation solutions*

2.2.1. *Principles for renovation*

If the first essential requirement from Construction Products Regulation [17] “mechanical resistance and stability” is fulfilled, in most cases other essential requirements are more or less connected with building physics, indoor climate and energy performance.

Our survey of studied houses showed different needs for renovation:

- Structural aspects:
    - o renovation of basement (filling cracks between stones, replacing (adding) waterproofing between basement and external wall, reducing the humidity level in crawl space);
    - o replacing damaged floor beams and rotted wooden logs in external walls;
    - o replacing damaged wall cladding, replacing water flashings;
    - o replacing or renovating old windows;
    - o repairing or replacing roof cover and beams, adding rainwater drainage system;
    - o renovation of old stoves and chimneys (fire safety).

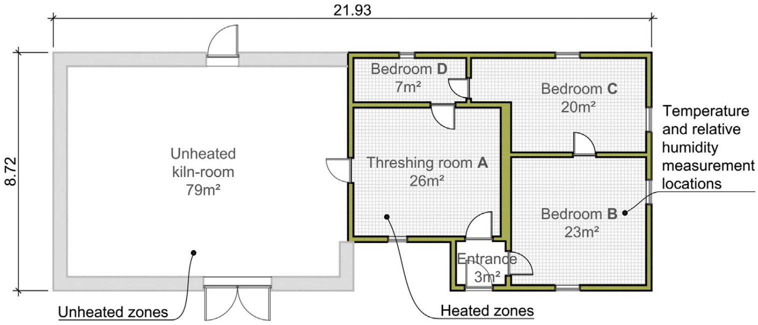

Fig. 2. Plan of the example Estonian house.

- Building physical and indoor climate aspects:
  - o improving thermal resistance of the building envelope (ceiling, external walls, floor, and windows);
  - o adding a ventilation system with heat recovery;
  - o minimising the influence of thermal bridges and tightening the areas of air leakage.
- Energy performance and building service related aspects:
  - o improving thermal resistance of the building envelope;
  - o increasing the efficiency of the energy source and the heating system;
  - o adding a ventilation system with heat recovery.

The list above shows that it is possible to devise renovation measures that would cover different renovation needs. For example, if there is a need for replacing damaged wall cladding, it is rational to do it with additional thermal insulation. For selecting energy renovation measures, simulations were done in different phases under standard uses of the house:

- Basic situation: non-renovated ("as built") conditions;
- Influence of a single energy-renovation measure to find out its relative importance:
  - o measure concentrated on an effective thermal envelope;
  - o measure concentrated on effective building service systems (HVAC);
  - o measure concentrated on the energy source and the use of renewable energies.
- Energy-renovation packages were calculated for different scenarios for different energy saving levels.
  - o Package I: to save cultural heritage values the least changes to the external appearance of the house were the purpose: insulation is replaced starting from the less visible parts of the external surface, such as roof, floor, windows etc. (concentrating on the preservation of external milieu value upon the insulation of the building envelope). The replacement of old structures is allowed. In that case, it is necessary to copy the dimensions and proportions of the original building features.
  - o Package II: concentrating on the improvement of thermal comfort (decreasing thermal transmittance of structures $U < 0.7\,\mathrm{W/(m^2\,K)}$ to avoid asymmetric radiation and draft). Energy-renovation starts with the insulation of the building envelope and later moves into service systems.
  - o Package III: improvement of energy performance starts from building service systems and later moves into the structures.

2.3. Assessment of energy performance of buildings

2.3.1. Energy performance requirements

The energy performance of buildings in Estonia [18] and in Finland [19] is expressed as annual primary energy consumption (PE, $\mathrm{kWh/(m^2\,a)}$) and in Sweden [20] as the use of delivered energy for space heating and heating of ventilation air, the delivered energy includes also energy for heating of domestic hot water, fans and pumps (DE, $\mathrm{kWh/(m^2\,a)}$). The PE is calculated from the total delivered energy by using energy carrier factors for fossil fuels (1.0), wood and biofuels (EST: 0.75, FIN: 0.5, SWE: wood 0.92, pellet 0.97), and electricity (EST: 2.0, FIN: 1.7, SWE: 2.32) [31]. Additionally, PE includes energy for lighting and household electricity. To enable the comparison of renovation measures in different countries, the reduction of the annual delivered energy and the energy performance value from original levels was used:

- 20% reduction from the original PE (background: renovation requirement for the Finnish sample house [21]).
- 60% reduction from the original PE (leads to the requirement of major renovation for the Estonian sample house [18]).
- 80%/88% reduction from the original DE (leads to major renovations for the Swedish sample house (80% when electricity is not used for heating; 88% reduction in case electricity is used for heating) [20]).

2.3.2. Calculation of energy performance of houses

The renovation alternatives of energy performance were modelled using the IDA indoor Climate and Energy 4.2 (IDA-ICE) building simulation software. This software allows the modelling of a multi-zone building, HVAC-systems, internal and solar loads, outdoor climate, etc. and provides simultaneous dynamic simulation of heat transfer and air flows. The performance of IDA-ICE is studied and validated for example in [22–25].

Target indoor temperatures were +21 °C for the heating season. Window airing was used when the indoor temperature exceeded 27 °C (no mechanical cooling systems). The use of domestic hot water (DHW) was 45 l/(d·person). The number of persons was counted based on bedrooms: the number of persons was equal to the number of bedrooms +1. The difference in the temperatures of domestic hot and cold water was 50 °C.

Internal heat gains were as follows:

- Inhabitants: $\sim 10.5\,\mathrm{kWh/(m^2\,a)}$. Heat from inhabitants was calculated using $2\,\mathrm{W/m^2}$ and 80 W/person using ISO 7730 standard (1.2 met, 0.7 clo).
- Appliances, equipment: $12.6\,\mathrm{kWh/(m^2\,a)}$. Heat from appliances and equipment was calculated using $2.4\,\mathrm{W/m^2}$ and the usage rate was 0.6. The use of electricity for appliances and equipment was 30% higher (some of energy leaves the building from sewerage).
- Lighting: $7\,\mathrm{kWh/(m^2\,a)}$. Heat from lighting was calculated using $8\,\mathrm{W/m^2}$ and the usage rate was 0.1.

Ventilation airflow was $0.35\,\mathrm{l/(s\,m^2)}$ for a non-renovated case and in single renovation measures without improvement of ventilation, representing indoor climate category III (an acceptable, moderate level of expectation for indoor climate [26]). Because the ventilation performance was insufficient in most energy renovation packages of rural houses, the renovated ventilation was represented by indoor climate category II (normal level of expectation for indoor climate: $0.42\,\mathrm{l/(s\,m^2)}$).

The air tightness of every building was measured with the standardised fan pressurisation method [27], using "Minneapolis Blower Door Model 4" equipment with an automated performance testing system (Table 1). Infiltration rate was calculated by a simulation model using the average air leakage rate from the studied countries (see Table 1), indoor/outdoor air tightness (depends on the temperature), building geometry, pressure constants [28] and wind speed. 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 up to 60%: 5% at the insulation of stone walls, 10% at the renovation of windows and additional thermal insulation for slab on the ground, 15% in case of new windows, insulation of attic floor and base floor with ventilated crawl space, 20% at the insulation of wooden log walls. The thermal transmittance of every envelope part was calculated based on the technical survey of houses.

Annual efficiency of the energy source and heat distribution systems is presented in Table 2.

From IDA-ICE the "System Energy" table about the complete house and the multi-zone report about all the heated rooms was used as output information. The influence of the heating source was calculated with Microsoft Excel.

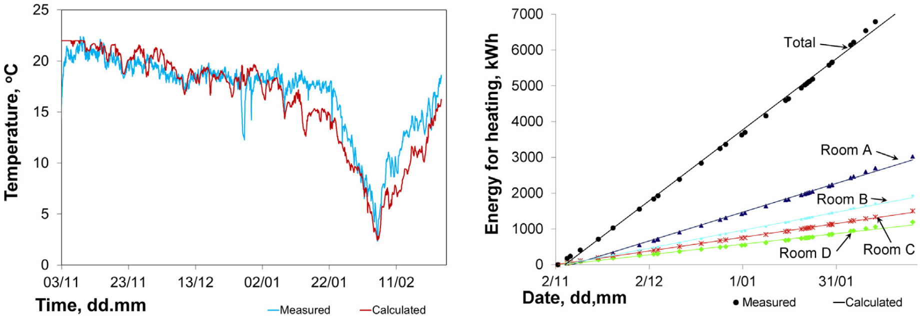

Fig. 3. Measured and calculated indoor temperatures (left) and used energy for room heating (right) during measurement period in different rooms (locations see Fig. 2).

Table 2
Annual efficiency of energy source and heat distribution systems [29], [30].

		Efficiency	
		Room heating	DHW
Energy source	Wood burning stoves, original/new or renovation	0.6/0.8	
	Wood-pellet boiler	0.85	0.85
	Oil/gas condensate boiler	0.9	0.9
	Electricity	1.0	1.0
	Exhaust air heat pump (min. ex, air temp +1 °C)	2.1	2.1
	Air-water heat pump, radiators (45/35 °C)	2.4	1.8
	Air-air heat pump	2.8	
	Ground source heat pump, radiators (45/35 °C)	2.9	2.3
Heat distribution	Stoves	0.85	
	Hydronic radiators	0.85	
	Electric radiators	0.95	

At room heating with stoves or air-air heat pump, DHW was heated with an electrical boiler. In all the other cases the same energy source was used for room heating and DHW. As floor heating requires the rebuilding of all floors, energy renovation measures with a boiler and a heat pump were calculated with radiator heating.

2.3.3. *Validation of indoor climate and energy simulation models*

Simulation models were validated based on field measurements. For example, when the simulation model of the example Estonian house (Fig. 2, the house originally heated by wooden stoves) was validated, it was heated by electric radiators during a four-month winter period. During that period, the house was not used for living, which guaranteed good understanding about the energy use in house. Fig. 3 shows the measured and calculated indoor temperatures (left) and the energy used for room heating (right) during the measurement period. The temperature drop in Fig. 3 was caused by too low heating power during a cold week. Good agreement between the measured and the simulated indoor temperatures (1.2 °C degrees average difference) and energy (measured value 3% higher) for heating allowed us to continue simulations to find the energy renovation measures.

3. Results

3.1. *Individual energy renovation measures*

To show the influence of individual energy renovation measures on the buildings, they were added one by one to the sample houses (Table 1) and their impact was calculated on standard building usage, see Table 3. The energy saving was compared with the base case from each country.

3.2. *Energy renovation packages*

To achieve energy saving purposes, individual energy saving measures appear inadequate; a combination of different energy saving measures is needed. Renovation packages were calculated for different scenarios for different energy saving levels (Table 4).

Finally, to find out the influence of climate and building typology, all sample buildings were calculated with a similar energy renovation package (W1.1 + EW120 + AF420 + BF200 + VHR80) on three climates and four heat sources: DE in Fig. 4 and PE in Fig. 5. Similar climates were used to calculate the base case (not renovated–for comparison) and renovated case.

The appearance of the building could have minimal changes when only the building service systems (heating and ventilation system, energy source) are improved. Merely the improvement of the ventilation system (VHR80) and the use of the best energy source (GSHP) can improve the energy performance by close to 50% of the delivered energy:

- Estonia: PE = 273 kWh/(m^2 a) (−46%); DE = 112 kWh/(m^2 a) (−78%) (GSHP used);
- Sweden: PE = 320 kWh/(m^2 a) (−47%); DE = 113 kWh/(m^2 a) (−80%) (GSHP used);
- Finland: PE = 228 kWh/(m^2 a) (−37%); DE = 373 kWh/(m^2 a) (−34%) (WPB used).

4. Discussion

Energy-renovation alternatives for three different historic rural houses in the Baltic Sea region were analysed. The results show the dependence of energy savings on energy saving targets, typology of the building, thermal transmittance of the original structures, and building service systems.

Targets for energy savings are usually derived from the macro-energy principles [1], and do not take into account specific peculiarities of buildings officially protected as part of a designated environment, or because of their special architectural or historical merit, which usually renders them exempt from general requirements on the energy performance of buildings. Cultural heritage buildings deserve a special approach in addressing the energy performance of buildings in order not to lose their value. Nevertheless, users and owners of these buildings ask for solutions in energy savings.

Improvement of building service systems (ventilation and heating systems) account for one of the largest energy saving potential (up to 47% in the primary energy and up to 80% in the delivered

Table 3
Influence of individual energy-renovation measures on the level and percentage reduction of annual delivered energy (DE, kW/(m^2 a)) and primary energy (PE, kW/(m^2 a)) (described in Section 2.3.1).

Energy-renovation measure	DE, kW/(m^2 a) Reduction from base case, %			PE, kW/(m^2 a), Reduction from base case, %		
	EST	FIN	SWE	EST	FIN	SWE
Base case: non-renovated/original ("as built") house						
Original structures, no heat recovery for ventilation, old wood burning stoves, DHW with electricity	512 ± 0%	566 ± 0%	553 ± 0%	510 ± 0%	358 ± 0%	603 ± 0%
Improvement of indoor climate						
VHR0: Class II ventilation (without heat recovery)	535 + 4%	588 + 4%	572 + 3%	528 + 4%	369 + 3%	622 + 3%
Renovation of thermal envelope (no improvement of service systems)						
W1.6: Renovation of original windows: old frame, new low-ε glasses and sealants: U = 1.6 W/(m^2 K)	499 – 3%	540 – 5%	525 – 5%	500 – 2%	345 – 4%	577 – 4%
W1.1: New windows, outlook similar to original: U = 1.1 W/(m^2 K)	490 – 4%	521 – 8%	510 – 8%	493 – 3%	336 – 6%	564 – 7%
W0.8: New windows, outlook similar to original: U = 0.8 W/(m^2 K)	487 – 5%	513 – 9%	502 – 9%	491 – 4%	332 – 7%	556 – 8%
EW20: Additional external thermal insulation for walls: 20 mm sheathing	446 – 13%	529 – 6%	404 – 27%	460 – 10%	340 – 5%	466 – 23%
EW70: Additional external thermal insulation for walls: 50 mm insulation + 20 mm sheathing	409 – 20%	499 – 12%	338 – 39%	432 – 15%	325 – 9%	406 – 33%
EW120: Additional external thermal insulation for walls: 100 mm insulation + 20 mm sheathing	392 – 23%	482 – 15%	312 – 44%	420 – 18%	316 – 12%	382 – 37%
EW170: Additional external thermal insulation for walls: 150 mm insulation + 20 mm sheathing	376 – 27%	473 – 16%	299 – 46%	408 – 20%	312 – 13%	371 – 39%
EW220: Additional external thermal insulation for walls: 200 mm insulation + 20 mm sheathing	368 – 28%	467 – 17%	291 – 47%	402 – 21%	309 – 14%	363 – 40%
AF220: Additional thermal insulation for attic floor: 200 mm insulation + 20 mm sheathing	455 – 11%	497 – 12%	525 – 5%	467 – 8%	324 – 10%	578 – 4%
AF420: Additional thermal insulation for attic floor: 400 mm insulation + 20 mm sheathing	440 – 14%	483 – 15%	522 – 6%	456 – 11%	317 – 12%	574 – 5%
BF200: Additional thermal insulation for base floor: 200 mm insulation	464 – 10%	507 – 11%	529 – 4%	473 – 7%	329 – 8%	581 – 4%
BF300: Additional thermal insulation for base floor: 300 mm insulation	458 – 11%	496 – 12%	526 – 5%	469 – 8%	324 – 10%	578 – 4%
AT30: Improvement of airtightness of the envelope by 30%: (tightening of windows and building envelope)	494 – 4%	548 – 3%	536 – 3%	497 – 3%	349 – 2%	589 – 2%
AT60: Improvement of airtightness of the envelope by 60%: (extremely careful tightening of windows and building envelope)	472 – 8%	530 – 6%	517 – 7%	480 – 6%	340 – 5%	572 – 5%
Renovation of ventilation systems (no improvement of structures)						
VHR60: Supply-exhaust ventilation with heat recovery 60% and Class II ventilation	462 – 10%	495 – 12%	498 – 10%	477 – 6%	348 – 3%	568 – 6%
VHR80: Supply-exhaust ventilation with heat recovery 80% and Class II ventilation	442 – 14%	485 – 14%	489 – 12%	462 – 9%	331 – 8%	547 – 9%
Renovation of energy sources (no improvement of structures)						
WS: New or renovated wood burning stoves	417 – 19%	440 – 22%	422 – 24%	440 – 14%	295 – 18%	483 – 20%
WB: Wood burning boiler	459 – 10%	480 – 15%	445 – 18%	402 – 21%	272 – 24%	484 – 20%
WPB: Wood-pellet boiler	406 – 21%	426 – 25%	402 – 27%	362 – 29%	246 – 31%	459 – 24%
OB: Oil condensate boiler	383 – 25%	404 – 29%	380 – 31%	408 – 20%	423 + 18%	440 – 27%
ER: Electrical radiators	316 – 34%	333 – 41%	310 – 44%	681 + 34%	566 + 58%	777 + 29%
AWHP: Air–water heat pump	174 – 66%	195 – 66%	171 – 69%	397 – 22%	331 – 7%	455 – 25%
AAHP: Air–air heat pump	245 – 52%	258 – 54%	231 – 58%	540 + 6%	438 + 22%	594 – 1%
GSHP: Ground source heat pump	129 – 75%	147 – 74%	124 – 77%	307 – 40%	251 – 30%	347 – 42%
SC: Solar collectors for DHW	485 – 5%	547 – 3%	543 – 2%	455 – 11%	326 – 9%	579 – 4%
PV: PV-panels	512 ± 0%	556 – 2%	549 – 1%	503 – 1%	342 – 5%	585 – 6%

Table 4
Energy-renovation packages for different energy saving levels and countries.

Energy saving level, country, and renovation package		Delivered energy, kWh/(m^2·K) / decrease from base case, %	Primary energy, kWh/(m^2·a) / decrease from base case, %	Energy-renovation measures: Windows			External walls					Attic floor		Base floor		Venti-lation		Energy source				
				W1.6	W1.1	W0.8	EW20	EW70	EW120	EW170	EW220	AF220	AF420	BF200	BF300	VHR60	VHR80	WS	WPB	GSHP	SC	PV
-20% (PE)	EST, I	355 / -31%	397 / -22%	×									×				×					
	FIN, I	392 / -31%	284 / -21%									×		×			×					
	SWE, I	409 / -26%	474 / -21%	×								×		×			×					
	EST, II	355 / -31%	398 / -22%	×			×					×		×								
	FIN, II	415 / -27%	283 / -21%		×		×					×		×								
	SWE, II	391 / -29%	457 / -24%				×					×		×								
	EST, III	363 / -29%	403 / -21%													×		×				
	FIN, III	387 / -32%	282 / -21%														×	×				
	SWE, III	383 / -31%	463 /-23%													×		×				
-60% (PE)	EST, I	75 / -85%	199 / -61%	×								×		×			×			×	×	
	FIN, I	205 / -64%	144 / -60%			×			×				×		×		×		×			
	SWE, I	80 / -86%	244 / -60%			×							×	×			×			×		
	EST, II	124 / -76%	189 / -63%		×					×			×	×			×				×	
	FIN, II	207 / -63%	145 / -60%			×				×			×	×			×		×			
	SWE, II	153 / -72%	240 / -60%	×				×				×		×			×	×				
	EST, III	75 / -85%	199 / -61%										×	×			×			×	×	
	FIN, III	222 / -61%	139 / -61%		×								×		×		×		×		×	×
	SWE, III	76 / -86%	233 / -61%			×							×	×			×			×	×	
-80%*	EST, I	40 / -92%	122 / -76%			×					×		×		×		×			×	×	×

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[*] Heating source other than electricity (wood, pellet, gas, oil).
[**] Heating source is electricity (direct electricity, heat pumps).

energy) because of the low energy efficiency of existing systems. These measures usually have lower influence on the appearance of the building. The changing of service systems, such as new radiators, ventilation channels, repairs of interior finishing, could influence the interior of the building to a much larger extent. Energy carrier factors caused the differences between countries when only service systems were improved. Therefore, the improvement value of service systems partially depends on the political developments.

Of building envelopes, the insulation of an external wall has the largest individual energy saving potential. This is partly due to the high thermal transmittance of original external walls and partly due to the relatively large area of the external walls of the whole building envelope. In the compared stone houses with the highest thermal transmittance the additional insulation of the external wall improved the energy performance (both DE and PE) twice in Estonian and three times in Finnish houses. As old houses are quite air-leaky, the improvement of airtightness could be a rather invisible energy saving measure. Nevertheless, from the practical building technology point or view, it is rational to combine insulation with the air-tightening of the building envelope.

If the rural houses are usually not listed as monuments, the change of original materials is not such a dramatic problem and

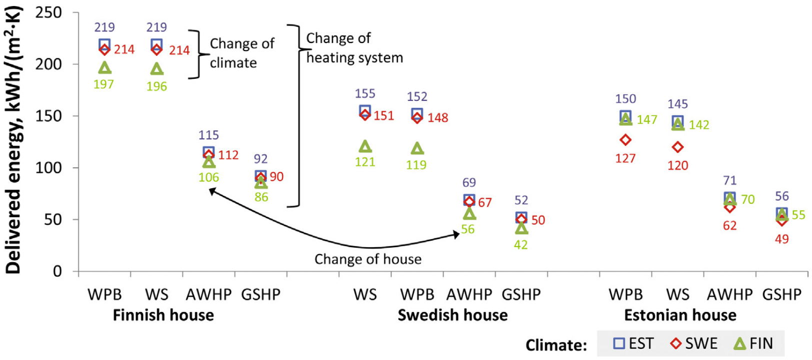

Fig. 4. The influence of climate, heating source and building typology on the delivered energy usage of renovated houses.

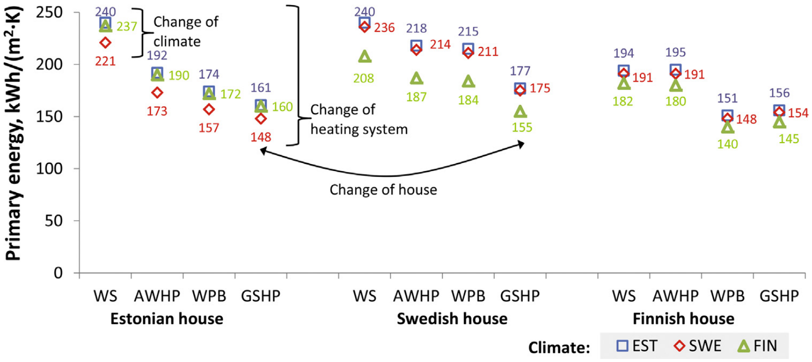

Fig. 5. The influence of climate, heating source and building typology on the primary energy usage of renovated houses.

it is more important that the original external appearance stays similar after energy renovations to keep the rural milieu. Due to restrictions on the changes of appearance, houses listed as monuments have reduced possibilities of energy savings, as on average it is possible to save 30% of energy with the improvement of external walls and windows.

In the countries compared, energy-renovation measures are selected on significantly different bases when following the local regulations [18,20,21]: when following Finnish regulations, the external appearance of a house may easily remain untouched; when following Estonian regulations, only minor changes on the external side of a house are needed; but it is impossible to achieve the target values of Swedish regulations without major renovation of the externally visible part of a house. It shows the need to distinguish different levels for the energy-renovation in national regulations.

Firstly, the indoor climate and thermal comfort were increased by installing a mechanical ventilation system following the airflow rates at a normal level of expectation for indoor climate. The balanced supply-exhaust ventilation system with heat recovery of at least 60% is proposed for installing the new ventilation system. Secondly, the thermal transmittance of the envelope was decreased to avoid asymmetric radiation and draft (in energy-renovation package II and combinations with higher energy improvement). Thirdly, the old heating system is renovated or replaced with devices easier to use and less time consuming (concerning the heating process) for the inhabitant by increasing the efficiency of the energy source and the heating system at the same time. The increase of thermal and living comfort should be of higher importance to the inhabitants than the initial cost of the renovation works, but it is complicated to combine the living quality with energy improvements in the calculations.

Figs. 4 and 5 show the influence of the climate, the heating system and the building typology. The same energy packages in different countries showed a lower influence from the climate (DE: 7–25%, PE: 6–19%), because the climate conditions in the studied locations are similar. Higher influence was found from the building typology (DE: 38–75%, PE: 7–36%). Although all the houses were old single family houses, the measures and the construction materials used were different, meaning also significant variations in energy performance values. Nevertheless, the energy source (DE: 88–114%, PE: 58–73%) had the highest influence on energy savings, meaning that replacing the old ineffective heating sources with more efficient ones can give the largest saving in a cold climate zone in every single family house.

5. Conclusions

The survey of the studied houses indicated that renovations relate to the diverse aspects of the structure, building physics and indoor climate, as well as energy performance and building services. For the improvement of energy performance, different renovation measures are possible. To make historic rural houses more energy efficient and to improve the indoor climate, different alternatives, such as the renovation of their thermal envelope, heating and ventilation systems, can be used. Additionally, the modern approach of renewable energies is a potential alternative.

In the cultural-historic and milieu valuable buildings, special attention should be paid to the preservation of cultural heritage value. Therefore, selected technical solutions should be more suited for the traditional houses and landscape. The energy performance analysis conducted in this study indicated that it is possible to realise national requirements for the energy performance of buildings with a smaller or larger effect on the appearance of the house.

The analysis showed that the improvement of building service systems and the energy source produces the largest energy saving potential. With a minimal influence on the appearance, this is a potential starting point to improve the energy performance and indoor climate of the building. Because national energy saving targets cannot be achieved by an improvement of building service systems only, the improvement of the building envelope is required.

The building envelope of old rural houses needs improvement also due to high thermal transmittance and air leakage. The insulation of the external wall has the largest single structural energy saving potential partly due to its high thermal transmittance and partly due to the relatively large area it comprises.

To achieve national energy performance targets, three energy performance levels with three different renovation strategies (minimal influence on the appearance of the house, improvement of thermal comfort, improvement of building service systems) were proposed. The results are useful to establish energy performance requirements for historic rural houses and informative to the final stakeholders.

Acknowledgment

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PAPER VI

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Field Study of Airtightness of Traditional Rural Houses in Estonia

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Abstract
Air leakage through the building envelope can lead to problems related to hygrothermal performance, health, energy consumption, the performance of ventilation systems, thermal comfort, noise, and fire resistance.

A field measurement study of air leakage was conducted on 48 traditional rural houses. The houses were classified according to age, finishing and building technology. Using a standardized building pressurization technique, the air leakage rate of each house was determined. In eleven of the selected houses the air change rate was determined also using tracer gas method during one month period in summer and in winter. To determine typical air leakage places and their distribution, an infrared image camera was used.

The mean air leakage rate at the pressure difference of 50 Pa in the database was 15 $m^3/(h \cdot m^2)$*. The mean air change rate at the pressure difference of 50 Pa in the database was 21 ach. The average air change rate during one month period in summer of normal usage was 0.57 ach. It was found that the internal finishing of the wall with plywood or plaster plays a significant role in the condition of the air leakage of the building envelope.*

The typical air leakage places in the studied houses were: doors and windows, external wall and ceiling joints, external wall and floor joints, and cracks between logs.

The results of the study can be utilised in working out renovation solutions for traditional rural houses in Estonia and in northern Baltic Sea region.

Keywords – air leakage; measurements; rural houses; energy consumption

1. Introduction

Uncontrolled air movement through a building envelope leads to problems related to the hygrothermal performance, health, energy consumption, performance of the ventilation systems, thermal comfort, noise and fire resistance. Air leakage through a building envelope depends on the result of air-pressure differences across the envelope, the distribution of air leakage places and the airtightness of the building envelope.

Air and moisture convection through the building envelope may cause severe moisture loads imposed on the structure [1]. Indoor air exfiltration in cold climates may cause moisture accumulation or condensation [2, 3], leading to microbial growth on materials, change of the properties of the material or even to structural deterioration. Air leakage through a building envelope could introduce outdoor or crawl space airborne pollutants [4] as well as radon gas into the indoor air [5]. Uncontrolled air leakage results in an increased air change rate and energy use [6]. The distribution of air leakage places affects infiltration and air pressure conditions in buildings.

The study has three main objectives:

- to study the airtightness and air leakage places of the building envelope of traditional rural houses;
- to study the normal air leakage rate measured using passive tracer gas technique during normal usage of houses;
- to analyze the dependency on normal air leakage and air tightness of the building envelope.

Field measurements of the airtightness and thermography measurements have been carried out in 48 traditional rural houses in Estonia. Passive tracer gas measurements have been carried out twice (during summer and winter) in eleven houses from the previous measurement selection.

2. Methods

2.1 Studied Houses

Studied houses were typically traditional threshing barn dwellings, mainly built between 1900 and 1940. The average floor area of the studied houses was 82 m^2; the average volume was 197 m^3. The selection of houses was made considering the construction, usage, heating system and location of the house. There was an equal number of continuously used, periodically used/heated and unused/unheated (summer cottages) houses.

The houses were usually 1-storey buildings with an attic (typically not used for living). The houses had a high roof with a roof angle of 45°, covered by thatch. External walls were made of horizontal wooden logs (diameter of roundwood elements was between 15 and 25 cm). Horizontal joints between the logs were tightened by tow or moss. In 45% of the houses external walls were internally covered with a layer of plaster or plywood; 71% of the houses had external timber cladding boards and 26% of the houses had external walls insulated with mineral wool. The majority of floor and ceiling structures consisted of wooden bearing beams and wooden boards. Wet rooms had concrete floors usually, often covered by ceramic tiles. Ceilings were covered with sand, sawdust or a layer of straw (mainly in the not yet renovated houses) or a layer of mineral wool insulation (in renovated houses). The windows of the studied houses mostly had wooden frames.

The studied houses had natural, passive stack ventilation. Few kitchens were supplied with a hood. In all of the houses (and most of the rooms) studied, windows could be opened for airing purposes. The majority of the studied houses were heated with a wood-burning stove. 50% of the houses had been renovated during the last 20 years and others had not been renovated or had been renovated more than 20 years ago.

2.2 Measurements

The air tightness of each building was measured with the standardized [6] fan pressurization method, using ‘‘Minneapolis Blower Door Model 4’’ equipment with an automated performance testing system. To determine the air tightness of the building envelope, depressurizing and pressurizing tests were conducted. All the exterior openings: windows and doors were closed; ventilation ducts and chimneys were sealed. Measurements were made at 10 Pa pressure difference step from 0 to 60 Pa. An exponential trend line was calculated according to the measurement points and an exact 50 Pa reading was taken from the trend line.

In addition to a short air leakage test, passive tracer gas method (described in standards [8, 9]) was used in selected houses to study the air leakage under everyday usage. Small perfluorocarbon tracer gas (PFT) samplers were distributed in the house. Two to eleven samplers were distributed per house depending on house volume and the number of rooms used, so that the emission was homogeneous in the whole building. The tracer gas was continuously released at a constant rate to the room air. Passive diffusion samplers were placed in each room to sample tracer gas at steady state room air concentration. A well-ventilated room gets a relatively low concentration, while a less well-ventilated room gets a higher concentration of tracer gas in the air. The measurement period in each house lasted 3…4 weeks, both during summer and winter period. After the sampling period, the samplers were capped and sent by mail to the laboratory for analysis. The measurement result constitutes an average value of the supply rate of outside air during the measurement period. The primary measured value is called “local mean age of air”, it is equal to the inverted value of the local air change rate of the building (used in this article). The inaccuracy of the PFT-method is approximately ±10…15 % (based on laboratory measurement protocols).

To determine typical air leakage places and their distribution, an infrared image camera FLIR Systems E320 was used. All the thermography tests were made during the winter period. The preferred difference between the indoor and the outdoor air temperature was at least 20ºC. Thermography investigations were done twice. First, to determine the normal situation, the surface temperature measurements were performed without any additional pressure difference. Next, to determine the main air leakage places, the 50 Pa negative pressure under the envelope was set with fan pressurization equipment. After the infiltration airflow had cooled the inner surface (~30…45 min) of the envelope, the surface temperatures were measured with the infrared image camera from the inside of the building.

3. Results

3.1 Air Tightness of Building Envelope

To compare air tightness of different buildings, the air flow rate at the pressure difference ±50 Pa was divided by the external envelope area (resulting air leakage rate at ±50 Pa, q_{50}-value) or by the internal volume of the building (resulting air change rate at 50 Pa, n_{50}-value). The results of air leakage rate and air change rate at ±50 Pa from fan pressurization measurements are presented in Fig. 1.

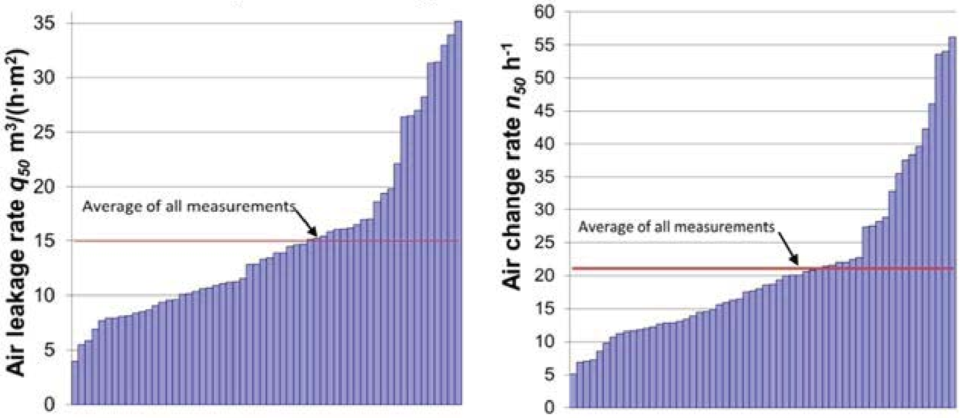


Fig. 1 Air change rate and air leakage rate in all measured houses

According to Fig. 2 there was almost no difference when the house was built. Based on 58 measurements, the air tightness of rural houses made of logs has not changed during two centuries: q_{50} = 15 m^3/(h·m^2) (values between 3.9…35 m^3/(h·m^2)); mean air change rate was n_{50} =21 h^{-1} (values between 5.1…56 h^{-1}).

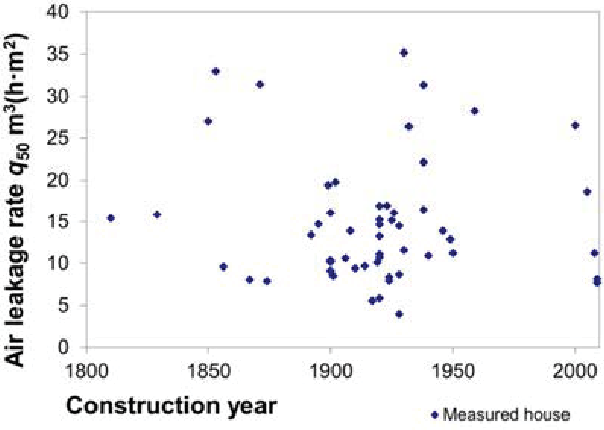


Fig. 2 Correlation of air leakage rate and construction year in all measured houses

Fig. 3 shows the comparison of air tightness within different subdivisions. Internal covering of external wall has a significant influence on the airtightness of the building envelope (in almost half of the houses the external walls were covered with a layer of plaster or plywood on the inside). The houses where the external walls were covered on the inside had a 25% lower air leakage rate. Among a equal number of renovated and unrenovated houses (the house was considered as renovated when substantial renovations had been performed on it during past 20 years), there was no influence of renovation works to building air leakage. There was also no difference in the air leakage of the house when external wooden wall cladding was present (2/3 of the houses had external cladding, sometimes with sheathing paper on the log surface) or the house was additionally insulated (1/4 of the houses were additionally insulated).

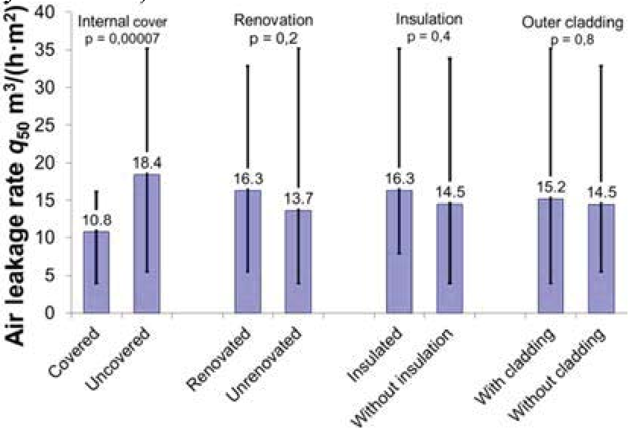


Fig. 3 Correlation of air leakage rate and construction year in all measured houses

3.2 Infiltration During Normal House Usage

The air change during normal house usage (ACH) was measured with passive tracer gas method in 10 houses during 32…35 days in the summer period and in 11 houses during 21…26 days in the winter period. Three houses were divided into sections according to usage profile and air tightness was measured separately in these sections, and the infiltration results were presented separately. The measurement results are shown in Table 1.

Average air change rate during normal house usage was 0.57 h^{-1} (average value during summer and winter was the same). Minimum air change rate was 0.16 h^{-1} (in summer) and maximum air change rate was 1.22 h^{-1} (in winter). The minimum and maximum values were measured in the same house at different times, based on this and other results there is no direct correlation between airtightness and natural infiltration of the house.

The average infiltration rate correlates almost linearly with the building leakage rate in most of the cases [10]. Because of this, the infiltration rate can be roughly approximated by the standard correlation dividing the building leakage rate n_{50} by a case-dependent denominator x (1).

$$n_{\text{inf}} = \frac{\mathrm{n}_{50}}{\mathrm{x}} \qquad (1)$$

The factor x is the product of several correction factors (using the principle shown in [11]): climate zone, wind condition, leakage distribution, number of stories, flow exponent, and ventilation balance [10].

Table 1. Measurement data

Code of house	**ACH, h^{-1} (summer)**	**ACH, h^{-1} (winter)**	Average n_{50}, h^{-1}	Average q_{50}, $m^3/(h \cdot m^2)$	Flow exponent
6103	**1.07**	**0.56**	12.8	10.6	0.737
6105	**0.21**	**0.64**	22.0	15.2	0.635
6106	**0.36**	**0.23**	11.9	8.5	0.637
6107	**0.60**	**0.85**	17.2	12.5	0.695
6107	**0.47**	**0.36**	23.7	16.1	0.658
6108	**0.41**	**0.26**	13.8	33.5	0.733
6108	**0.79**	**0.24**	44.0	10.1	0.572
6113	**0.50**	**0.68**	19.9	13.9	0.796
6114	**0.30**	**0.56**	11.2	9.4	0.725
6115	**1.16**	**0.72**	54.1	33.9	0.528
6117	**0.42**	**0.40**	5.1	8.7	0.782
6117	**0.43**	**0.49**	12.6	3.9	0.623
6117	**1.07**	**1.00**	18.7	14.5	0.720
6118	**0.16**	**1.22**	20.8	16.1	0.699

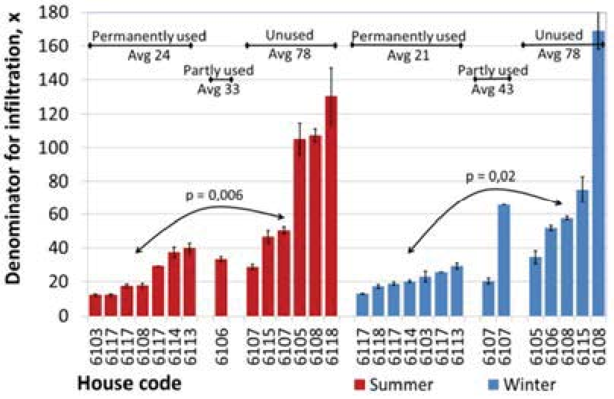


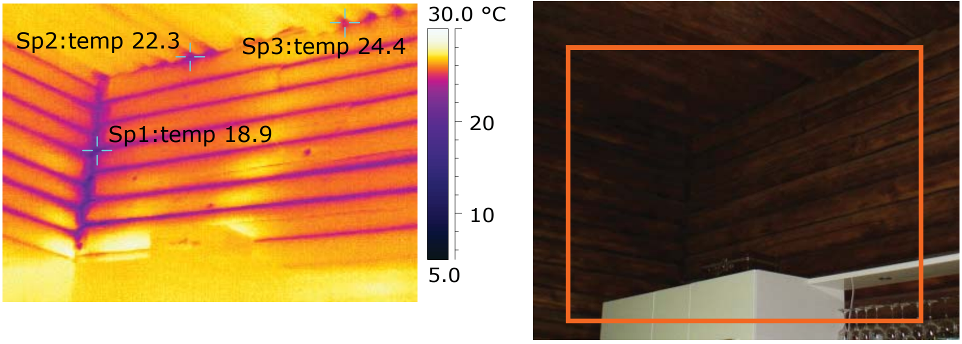
Fig. 4 Passive infiltration in houses with different usage profile in summer and winter

The most important factor that influenced air leakage in normal conditions was house usage, Fig. 4. The measured houses were divided into three groups: permanently used houses (usage 70…100% of the time), partly used houses (usage 30…70% of the time) and unused houses (usage below 30% of the time). Usage data was obtained from habitants.

Outdoor temperature conditions influence air pressure conditions and therefore also air leakage rate. Nevertheless, seasons have a smaller impact on the air leakage than house usage: average values were x = 24 in summer and x = 21 in winter in permanently used houses; in unused houses x = 78 both in summer and in winter. There were too few partly used houses to reach any conclusions. There was a statistically significant difference between permanently used and unused houses (respectively p = 0.006 and p = 0.02 in summer and winter), the factor x is more than three times smaller in permanently used houses than in unused houses: natural infiltration is three times lower in unused houses compared to permanently used houses.

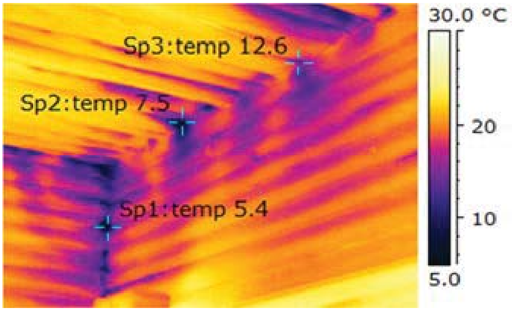
3.3 Typical Air Leakage Locations

To determine typical locations of air leakage and their distribution, an infrared image camera was used. Figs. 5 and 6 show the examples of air leakage locations on the junction of the ceiling and the external wall.


Termocam image, ±0Pa

Photo

Termocam image, -50Pa



Outdoor temperature	+1.5 °C
Indoor temperature	+27.1 °C
Measured surface temperatures	
Sp1 (±0Pa)	18.9 °C
Sp2 (±0Pa)	22.3 °C
Sp3 (±0Pa)	24.4 °C
Sp1 (-50Pa)	5.4 °C
Sp2 (-50Pa)	7.5 °C
Sp3 (-50Pa)	12.6 °C

Fig. 5 Termocam image from junction of external wall and ceiling under normal conditions (upper left) termocam image after 50Pa depressure (lower left) with normal image (upper right) and numeric data (lower right).

Relative reduction of the surface temperature was used to determine air leakage locations. Relative reduction of the surface temperature (Δt_s, %) shows the relation between the indoor (t_{in}, °C) and outdoor (t_{out}, °C) air temperatures to the temperature difference between internal surface of the building envelope measured before (t_{si1}, °C) and after (t_{si2}, °C) the depressurization [12]:

$$\Delta t_s = \frac{t_{si1}-t_{si2}}{t_{in}-t_{out}} \times 100\% \qquad (2)$$

Typical air leakage places in the studied houses were:

- junction of the ceiling with the external wall (33%);
- junction of the floor with the external wall (14%);
- envelope surface (mainly cracks between logs) (20%);
- junction of external walls (9%);
- leakage around and through windows and doors (21%).

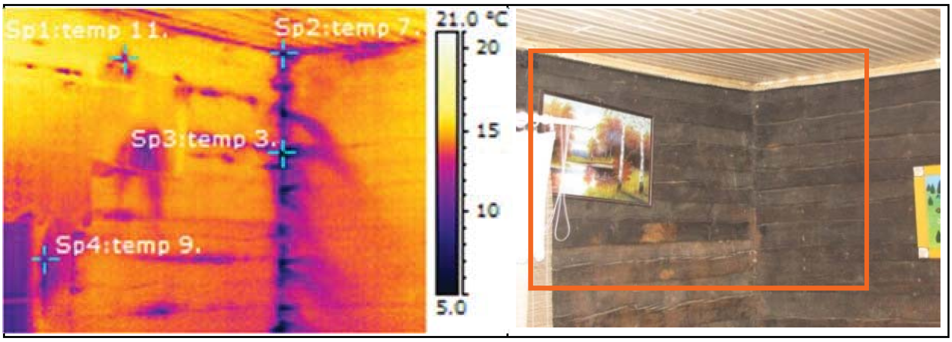


Fig. 6 Air leakage in the junction of external walls and though cracks between logs, termocam image (left) and photo (right).

4. Discussion

Air leakage of the building envelope of traditional rural houses is much larger than that of detached houses on average in Estonia.

Based on measurements in traditional rural houses with log walls (58 measurements), the average air leakage rate was $q_{50} = 15$ m^3/(h·m^2) and average air change rate was $n_{50} = 21$ h^{-1}. Previous study [13] about the airtightness of Estonian detached houses (114 measurements) showed that the average airtightness of a building envelope is 5.2 m^3/(h·m^2). Log houses were among the leakiest building types. Therefore, in energy calculations, air leakage should be calculated with larger air tightness value than the base value in Government Ordinance [14]: $q_{50} = 6$ m^3/(h·m^2) for new and $q_{50} = 9$ m^3/(h·m^2) for renovated houses.

Comparison of airtightness of the building envelope of renovated and unrenovated houses showed only minor differences. Contrary to expectation, air leakage rates of renovated houses were larger than unrenovated houses. This result can be caused by the following reasons:

- Originally, the external walls were often plastered from internally which has significant influence on the airtightness of the building envelope (see Fig. 3). During renovation works plaster was often removed for aesthetic reasons;
- Air leakage problems were unintentional and design, as well as, structural solutions did not concentrate directly on the reduction of air leakage. Therefore, we cannot see the influence of renovation works on the reduction of air leakage. Chan et al [15] showed that in the USA a higher reduction in the air leakage of the building envelope was achieved through weatherization assistant programs.

The analysis of the airtightness of the building envelope and air leakage of the house during normal use showed that the house usage significantly influences the house both during summer and winter. The natural infiltration was three times lower in unused houses compared to permanently used houses. This demonstrates a much larger influence than other factors shown by Jokisalo [10]. Typically, energy simulations are made without opening external doors and windows, or windows are opened only according to temperatures during summer. This may lead to differences in real and simulated air leakage rates.

5. Conclusions

The mean air leakage rate at the pressure difference of 50 Pa was 15 $m^3/(h \cdot m^2)$ (the min. being 3.9 $m^3/(h \cdot m^2)$ and max. 35 $m^3/(h \cdot m^2)$). The mean air change rate at the pressure difference of 50 Pa in all the databases was 21 h^{-1} (the min. being 5.1 h^{-1} and max. 56 h^{-1}).

According to the results, the most significant factor affecting the air tightness of the house was internal covering of external walls (a layer of plaster or plywood). The typical air leakage locations in the studied houses were: junctions between the ceiling or floor with the external wall, envelope surface, junctions between external walls, and leakage around and through windows and doors. More attention should be paid to the tightening of the building envelope.

The average air infiltration rate in such leaky houses during normal house usage was 0.57 h^{-1}. Together with increasing the air tightness of the building envelope more attention should be paid to the performance of ventilation.

House usage influenced significantly the correlation between the air infiltration rate and the airtightness of the building envelope. The infiltration was influenced less by seasons.

6. Acknowledgment

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