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Hygrothermal Performance of Prefabricated Timber Frame Insulation Elements for Deep Energy Renovation of Apartment Buildings

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Declaration:

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

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Puitkarkass-lisasoojustuselementide niiskustehniline toimivus suurpaneelelamute tervikrenoveerimisel

PEEP PIHELO

TALTECH KIRJASTUS

Abstract

Hygrothermal Performance of Prefabricated Timber Frame Insulation Elements for Deep Energy Renovation of Apartment Buildings

An improvement in energy performance of existing buildings is needed to fulfil the global energy saving policy objectives and ambitious visions of a better environment and use of smarter technologies. A highly insulated building envelope requires thoroughgoing hygrothermal analysis and design to avoid moisture damage. In the changing climate conditions, it means that the market participants must find up-to-date and efficient ways to improve the substance and quality of design and installation of buildings to meet the growing requirements of energy and hygrothermal performance of new and existing buildings.

An efficient way to accomplish deep energy renovation is to apply an integrated design process and to use prefabricated insulation elements paired with the expertise of hygrothermal performance. Hygrothermal performance of external walls of large concrete panel apartment buildings before and after additional insulation with prefabricated timber frame insulation elements under the cold and humid climatic conditions was studied with the aim to minimise the risk of the degradation of the structures.

In the course of fieldwork, evaluation and measurements of the condition of the building were performed before and after renovation. During reconstruction expertise and assessment of the taken measures were conducted. Laboratory tests were made to measure the properties of materials in original walls. Simulation models were calibrated, and series of analysis were performed to ensure the compliance of results to designed solutions.

The initial moisture content (IMC) and the risk of mould growth were analysed as the most important elements of hygrothermal design of additional insulation. The risk of mould growth in the structure can be minimised if the IMC of the original concrete large panel $w \leq 55$ kg/m^3 and polyethylene (PE) foil as the air and vapour barrier is used or if the IMC $w \leq 75$ kg/m^3 and the oriented strand board (OSB) as the vapour control layer is used or if the IMC $w \leq 110$ kg/m^3 and an air and vapour barrier with varying vapour resistance (water vapour diffusion resistance 0.2 m $\leq S_d \leq$ 5 m) on the mounted to the original wall timber frame element as the vapour control layer is used in combination with the insulation of the timber frame element (thermal resistance $R \geq 7.5$ m^2·K/W; $S_d \leq 0.5$ m) and wind barrier ($R \geq 0.8$ m^2·K/W; $S_d \leq 0.05$ m) layers covered with facade boarding.

A methodology to select the relevant combinations for deep energy renovation of large concrete panel buildings with prefabricated elements was proposed. Correspondingly, it was showed by calculations that the global cost was lower for solutions with some mould growth risk.

Nevertheless, there are still research and development tasks to be addressed in the future for the design and use of prefabricated timber frame insulation elements to be competitive on the market with the other conventional renovation solutions.

Keywords: *hygrothermal performance, moisture safety, quality commission, prefabricated timber frame insulation elements, nZEB renovation, deep energy renovation*

Kokkuvõte

Puitkarkass-lisasoojustuselementide niiskustehniline toimivus suurpaneelelamute tervikrenoveerimisel

Energiatõhususe poliitika ja parema keskkonna nimel ambitsioonikate visioonide elluviimiseks on vajalik olemasolevate hoonete energiatõhusust parendada arukamate tehnoloogiate kasutamisega. Madal- ja liginullenergiahoonete kavandamisel on niiskusekahjustuste vältimiseks vajalik välispiirete põhjalik niiskustehniline analüüs. Muutuvates kliimatingimustes tähendab see, et turuosalised peavad leidma asjakohaseid viise, kuidas parandada projekteerimise, disaini ja ehitustegevuse sisu ja kvaliteeti, et järgida karmistuvaid energiasäästu nõudeid ning tagada uute ja olemasolevate ehitiste niiskusturvaline toimivus.

Tõhus viis olemasolevate hoonete tervikrenoveerimise idee teostamiseks, rakendades samas niiskustehnilise projekteerimise alusteadmisi, on integreeritud projekteerimisprotsessi rakendamine ja tööstuslikult toodetavate puitkarkass-soojustuselementide senisest laialdasem kasutuselevõtt.

Käesolevas töös on uuritud raudbetoonpaneelidest korterelamute välisseinte niiskustehnilist toimivust külmas ja niiskes kliimas, enne ja pärast puitkarkass-lisasoojustuselementidega soojustamist, eesmärgiga minimeerida tarindite kahjustusi. Välitööde käigus teostati ehitise seisukorra uuringud ja mõõtmised enne ja pärast renoveerimist ning niiskusturvalisuse tagamiseks ka järelevalvet ja vajalike meetmete rakendamise hindamist rekonstrueerimistööde käigus. Korterelamu välisseina materjalide omaduste mõõtmiseks enne renoveerimistöid viidi läbi laboratoorsed uuringud. Kalibreeriti arvutisimulatsioonide mudelid ja tehti analüüsiseeriaid, et kontrollida tulemuste vastavust kavandatud lahendustele.

Niiskustehnilise projekteerimise kõige olulisemate elementidena uuriti välispiirde algset niiskussisaldust, hallituse tekke riske lisasoojustamisel ning määrati lubatud niiskuse tasemed. Hallituse tekke riski tarindis saab minimeerida, kui raudbetoonpaneeli algniiskus $w \leq 55$ kg/m^3 ja õhu- ja aurutõkkeks on polüetüleen (PE) kile või kui algniiskus $w \leq 75$ kg/m^3 ja aurutõkkeks on puitlaastplaat (OSB) või kui algniiskus $w \leq 110$ kg/m^3 ning olemasolevale seinale paigaldatud lisasoojustuselemendil on kasutatud varieeruva veeaurutakistusega õhu- ja aurutõkkemembraani (veeauru difusioonitakistus 0.2 m $\leq S_d \leq$ 5 m) koos lisasoojustuselemendi soojustuskihtide (soojustakistus $R \geq 7.5$ m^2·K/W; $S_d \leq 0.5$ m) ja tuuletõkkekihiga ($R \geq 0.8$ m^2·K/W; $S_d \leq 0.05$ m), mis on kaetud fassaadikattega.

Töö tulemusena on välja pakutud meetod tööstuslikult toodetavate puitkarkass-lisasoojustuselementidega raudbetoonpaneelidest hoonete tervikrenoveerimiseks sobivate kombinatsioonide valimiseks. Käsitelu tulemusel leidis kinnitust, et kogumaksumuselt odavam lahendus võib kaasa tuua suurema hallituse riski.

Seega tuleb edaspidi lahendada veel mitmeid teadus- ja arendustegevuse ülesandeid puitkarkass-lisasoojustuselementide kavandamisel ja kasutamisel, et olla turul konkurentsivõimeline teiste harjumuspäraste renoveerimislahendustega.

Märksõnad: *soojus- ja niiskustehniline toimivus, niiskusturvalisus, kvaliteedi tagamine, tööstuslikult toodetud puitkarkass-soojustuselemendid, liginullenergiahooneks renoveerimine, tervikrenoveerimine*

Contents

List of publications

The thesis is predominantly based on the data presented in the publications in the following peer-reviewed journals and conference proceedings:

I Pihelo, P., Kalamees, T., 2016. The Effect of Thermal Transmittance of Building Envelope and Material Selection of Wind Barrier on Moisture Safety of Timber Frame Exterior Wall. Journal of Building Engineering 6, 29–38

II Pihelo, P., Lelumees, M., Kalamees, T., 2016. Potential of Moisture Dry-out from Concrete Wall in Estonian Climate. In: Proceedings of the International RILEM Conference Materials, Systems and Structures in Civil Engineering MSSCE 2016, 22-24 Aug 2016

III Pihelo, P., Lelumees, M., Kalamees, T., 2016. Influence of Moisture Dry-out on Hygrothermal Performance of Prefabricated Modular Renovation Elements. In: Energy Procedia, SBE16 Tallinn and Helsinki Conference Build Green and Renovate Deep, 5-7 Oct 2016

IV Pihelo, P., Kalamees, T., Kuusk, K., 2017. nZEB Renovation with Prefabricated Modular Panels. In: Energy Procedia, 11th Nordic Symposium on Building Physics NSB2017, 11-14 June 2017, Trondheim, Norway, 1006–1011

V Pihelo, P., Kalamees, T., 2019. Commissioning of Moisture Safety of nZEB Renovation with Prefabricated Timber Frame Insulation Wall Elements. Wood Material Science and Engineering, published online: 03 July 2019

VI Pihelo, P., Kuusk, K., Kalamees, T., 2020. Development and Performance Assessment of Prefabricated Insulation Elements for Deep Energy Renovation of Apartment Buildings. Energies 13(7), 1709

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

Author's contribution to the publications

The author of the thesis is the principal author of all publications I–VI.

I The simulation model calibration and data analysis were performed by the author guided by the supervisor Prof. T. Kalamees. The proposed model was developed, and the article was written by the author and improved in cooperation with the supervisor Prof. T. Kalamees. The validated measurement data from Kalamees and Vinha (2003) was used to calibrate the simulation model.

II The case-study measurements were set up in situ, monitored and data were collected by the co-member of the research group PhD Simo Ilomets together with Prof. T. Kalamees. The measurements were analysed, and the simulation model was calibrated by the author with help by Magnus Lelumees, a MSc student. A hygrothermal simulation model was created and applied by the author and improved by the author in cooperation with the supervisor. The publication was written by the author in cooperation with the supervisor Prof. T. Kalamees.

III The simulations were carried out by the author and mass calculations were made by Magnus Lelumees. The publication was written by the author in cooperation with Prof. T. Kalamees.

IV The thermography field measurements and the analysis of the results were mostly carried out by the author. Energy calculations and analysis were performed with help by the co-author PhD Kalle Kuusk. The design solutions were devised and prepared by the author with the supervisor Prof. T. Kalamees. The results of the hygrothermal analyses made, and simulations and recommendations led to the final design and construction methods and were drawn out by the main designer of renovation of the pilot building, the design company Sirkel & Mall OÜ. The publication was written by the author of this thesis and improved in cooperation with the supervisor Prof. T. Kalamees.

V The field measurements were mostly carried out by the author, helped by MSc students and co-members of the research group. Data analysis was done by the author and looked over by the supervisor. The paper was written in cooperation with the supervisor Prof. T. Kalamees.

VI The field measurements were carried out and the proposed method was developed by the author. Data analysis was done by the author with help by the supervisor. Indoor climate and energy simulations and economic calculations were carried out by the author with help by PhD Kalle Kuusk. The paper was written in cooperation with the supervisor Prof. T. Kalamees.

Abbreviations

BIM	Building information modelling
CPR	Construction Products Regulation
CW	Cellulose wool
DHW	Domestic hot water
EN	European Norm (standard)
EPBD	Energy Performance of Buildings Directive
EPS	Expanded polystyrene
EPV	Energy performance value
ETAG	European Technical Approval Guideline
ETICS	External thermal insulation composite system
EU	European Union
HAM	Heat, air and moisture
HVAC	Heating, ventilation and air conditioning
ICC	Indoor climate class
IMC	Initial moisture content
ISO	International Organization for Standardization
MC	Moisture content
MRY	Moisture reference year
MVHR	Mechanical ventilation with heat recovery
MW	Mineral wool
nZEB	Nearly zero energy building
OSB	Oriented strand board
PCLP	Prefabricated concrete large panel
PE	Polyethylene
PUR	Polyurethane
TES	Timber-based element system
TRL	Technology Readiness Level
VHR	Ventilation with heat recovery
WDR	Wind-driven rain
3D	Three-dimensional

Symbols

A_w	Water absorption coefficient, kg/(m^2·s$^{0.5}$)
f_{Rsi}	Temperature factor, -
M	Mould index, -
q	Heat flux, W/m^2
q_{50}	Airflow leakage rate of the building envelope at 50 Pa pressure difference, m^3/(h·m^2)
R	Thermal resistance, m^2·K/W
RH	Relative humidity, %
S_d	Water vapour diffusion resistance, relative to equivalent air layer thickness, m
Z_p	Water vapour resistance with respect to partial water vapour pressure, m^2·s·Pa/kg
Z_v	Water vapour resistance with respect to humidity by volume, s/m
T	Temperature, K
t	Temperature, °C
U	Thermal transmittance, W/(m^2·K)
u	Moisture content by mass, kg/kg
w	Moisture content by volume, kg/m^3

Greek letters

Δ	Delta, difference, -
Δv	Indoor moisture excess, g/m^3
δ_v	Water vapour permeability with respect to humidity by volume, m^2/s
δ_p	Water vapour permeability with respect to partial water vapour pressure, kg/(m·s·Pa)
λ	Thermal conductivity, W/(m·K)
μ	Water vapour diffusion resistance factor, -
v	Vapour content, g/m^3
ρ	Density, kg/m^3
σ	Energy or moisture source; energy or moisture sink

Subscripts

c	Corrected
calc	Calculated
cond	Condensation
conv	Convection
crit	Critical
D	Declared
diff	Diffusion
e	External, outdoor
g	Gas
i	Internal, indoor
l	Liquid
lab	Laboratory
m	Mass
max	Maximum
min	Minimum
s	Surface
v	Vapour
w	Water

1 Introduction

A decrease in heat losses is obligatory for highly insulated and nearly zero energy buildings (nZEB). With reference to the European Union (EU) Energy Performance of Buildings Directive (2018/844/EU) and worldwide agreements (UNFCC 2012, 2015) we are looking for reduction of greenhouse gas (GHG) emissions and climate impact of the whole building stock. These expectations are driven by the need to optimise the use of resources, energy and time as well as by aspirations for a clean and healthy environment.

Future nZEB should be much more highly insulated than the buildings developed some years ago (Kalamees et al. 2016) to correspond to the future decarbonisation expectations. Energy performance requirements should be set with a perspective to achieve the cost-optimal balance between the investments involved and the energy costs saved throughout the lifecycle of the building. Kuusk et al. (2014) analysed the environmental impact of renovation of an old concrete element apartment building in Estonia and showed that the low-energy renovation had the lowest environmental impact when taking into account CO_2 emissions from the materials and the energy use in the building during 20 years. Totland et.al. (2019) analysed the effect of insulation thickness on the lifetime CO_2 emissions in Norwegian climate and found that the insulation increased embodied emissions, which were generally outweighed by the energy savings resulting from the increased insulation thickness. Ylmén et al. (2017) analysed the life cycle cost of buildings in Sweden and reported that although it is possible to optimise the insulation thickness in the building envelope and include secondary effects, the found optimal solutions will only be valid for the investigated building project. Resalati et al. (2019) searched an optimum insulation thickness considering the embodied energy and operational energy savings in the United Kingdom. For example, the median for glass wool insulation (which was used in an Estonian pilot building as well) shows a wide range between 200 mm and 360 mm as optimum with an identical level of carbon saving potential. In Estonia, climate is colder compared to the UK, and therefore, the optimal insulation thickness is higher. This indicates that the insulation thickness selected for the nZEB renovation building could be optimal from the life cycle point of view.

The EU Construction Products Regulation (CPR) (2011/305/EU) sets essential requirements for the safety of buildings and other construction works. The third requirement of Annex I of CPR prescribes that the construction works must be designed and built in such a way that they will, throughout their life cycle, not be a threat to the hygiene or health and safety of workers, occupants or neighbours, nor have an exceedingly high impact, over their entire life cycle, on the environmental quality or on the climate during their construction and use, also as a result of dampness in parts of the construction works or on surfaces within the construction works. Due to that, the design of hygrothermal performance and moisture safety is vital in the building process.

Designers, developers and owners are in quest of innovative ways to minimise operating costs and the environmental impact of buildings, while also increasing their functionality. Improved energy performance has been one of the driving forces for the renovation of old apartment buildings because energy related measures help to increase the cost-effectiveness of the whole renovation process and the upkeep of buildings (Jurelionis and Šeduikyte 2010, Matic et al. 2015, Hirvonen et al. 2019). Sartori and Hestnes (2007) analysed 60 case studies from nine countries on this topic and found that operational energy represents the largest part of the total energy use in residential buildings. Nemry et al. (2010) modelled the EU building stock and stated that heat loss through roofs and external walls and due to ventilation are significant for the majority of dwellings and in most cases bear an expressive potential for economically efficient environmental improvements, especially for additional insulation of the external envelope. Kuusk and Kalamees (2016), as well as Arumägi and Kalamees (2016) and Alev et al. (2014), showed that additional thermal insulation of the building envelope has an important role in improving the energy performance of the existing building stock in a cold climate. Because of high thermal transmittance, serious thermal bridges and high air leakage, improvement of the building envelope is a cost effective renovation measure in Estonia. As the area of external walls is relatively large in apartment buildings, additional thermal insulation of external walls has great influence on decreasing heat losses.

External thermal insulation composite systems (ETICS) have been used for decades for the renovation of masonry, concrete and other substrates (Ilomets and Kalamees 2013, Varela Luján et al. 2019). ETICS primarily fulfil the functions of thermal insulation and protection of buildings against the influences of weather (Ilomets et al. 2016). Many authors (Künzel et al. 2006, Ximenes et al. 2015, Sulakatko et al. 2017) have pointed out that durability issues, including the degradation of the surface and the ageing of the materials, are the most common problems in ETICS to deal with. Lack of automation and a high proportion of crafts will drive up the price, especially when demand is high (Kuusk et al. 2019).

An innovative approach to renovation is the application of prefabricated renovation elements, which has the potential to increase the renovation capacity, minimise renovation time on site and the disturbance for occupants and, at the same time, enhance quality and performance in terms of energy efficiency and indoor climate (Mjörnell 2011, 2016, Ott et al. 2013, Malacarne et al. 2016, Ruud et al. 2016, Sandberg et al. 2016). Using prefabricated insulation elements when renovating buildings is one of the main ways to standardise and industrialise renovation processes (Veld 2015).

1.1 Objectives and content of the study

In the thesis I analyse the most relevant properties and hygrothermal performance of prefabricated timber frame insulation elements for the deep energy and nZEB renovation of apartment buildings in a cold and humid climate. The main objectives of the thesis are:

- To analyse the parameters and constraints that have a critical effect on the hygrothermal performance of the timber frame exterior structures;
- To determine the critical initial moisture content (IMC) of a concrete facade and its dry-out capability;
- To link the IMC with the hygrothermal performance of additional exterior layers in the renovation of old apartment buildings with a concrete facade;
- To study the renovation of old apartment buildings to nZEB by using prefabricated insulation elements;
- To present a methodology of commissioning and moisture safety procedures in the course of designing and renovating an old apartment building by using timber frame insulation elements;
- To report the options for further (industrial) development of prefabricated insulation elements in combinations with most common material sets and with minimum moisture related risks for deep energy renovation.

A careful selection of materials allows designing moisture safe exterior walls and providing low thermal transmittance. It was found that the relative humidity (*RH)* and the risk of mould growth are higher, and the drying-out period is longer in walls with lower thermal transmittance when insulation thickness is the only changed parameter. Wind barriers with higher thermal resistance and water vapour permeability indicated a lower increase of mould growth risk in the structure in the course of the reduction of thermal transmittance. Therefore, considering also the apparent climate change, the building envelope of the future highly insulated nZEB requires a careful hygrothermal design. These aspects were studied in publication I and the results led to the supposition that with additional insulation of existing building envelopes consideration of moisture loads is extremely important.

In order to design a building envelope with a thicker thermal insulation layer and lower thermal transmittance, the designer has to solve many problems related to its hygrothermal performance. However, after the load-bearing requirements are met, other layers in the building envelope are usually designed according to the required thermal transmittance and visual appearance. But the design of the hygrothermal performance of the future nZEB and highly insulated building envelope based on the current knowledge and practices or solely on the stationary method (EN ISO 13788 2012) may most likely appear insufficient. The consideration of the IMC and its dynamics in structures has a critical role. The performance of the moisture content (MC) and the critical IMC levels of a concrete facade were studied in publication II. The influence of the drying out of moisture on the hygrothermal performance of insulation elements was studied and the results were discussed in publication III.

A renovation and design solution of the external envelope of an old apartment building with prefabricated timber frame insulation elements to the nZEB energy performance level was presented in publication IV.

The most relevant parts from existing moisture safety and quality assurance systems were combined and tested in the process of deep energy and nZEB renovation of an apartment building with prefabricated timber frame insulation elements. The measured data were used to calibrate the calculation model and to analyse the moisture loads and mould growth risks in publication V.

Several combinations of materials for developing prefabricated insulation elements were analysed considering the hygrothermal performance and the current minimum energy performance requirements with costs of the solutions. By different characteristics and with the help of measurements and building performance simulation software, visits to the factories, monitoring on the building site and workshops with interviews, the performance and mould growth risks of prefabricated elements for deep energy renovation were compared and working sets were presented as a primary evaluation tool for engineers and designers in publication VI.

The papers (I–VI) on which this thesis is mostly based can be characterised according to the well-recognised methodology of estimating technology maturity, i.e. Technology Readiness Levels (TRL) (see Figure 1.1). The TRL classification is implemented to demonstrate the research, system development, testing and launching. The TRL are described according to the Horizon2020 classification (TRL 2019) as follows:

- TRL 1 – Basic principles observed and reported;
- TRL 2 – Technology concept and/or application formulated;
- TRL 3 – Analytical and experimental critical function and/or characteristic proof of concept;

- TRL 4 – Component and/or technology validation in a laboratory environment;
- TRL 5 – Component and/or technology validation in a relevant environment;
- TRL 6 – System/subsystem model or prototype demonstration in a relevant environment;
- TRL 7 – System prototype demonstration in an operational environment;
- TRL 8 – Actual system completed and qualified through test and demonstration;
- TRL 9 – Actual system proven through a successful operational environment.

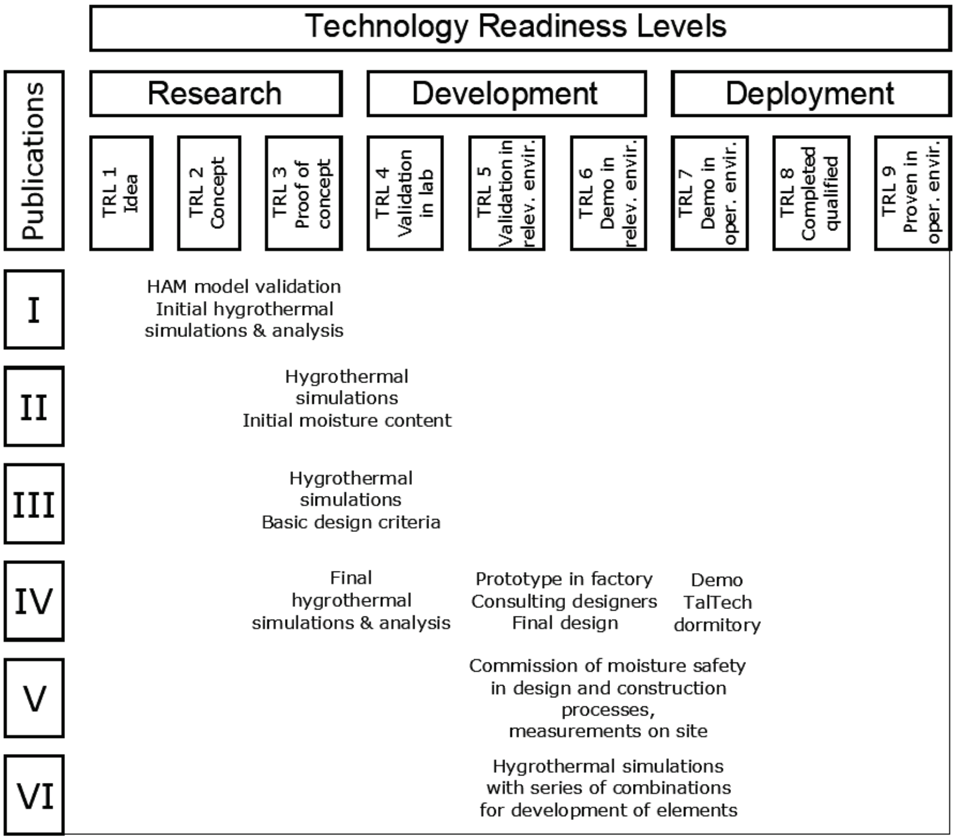


Figure 1.1 Activities in the current research according to the Technology Readiness Levels classification (TRL 2019).

1.2 Limitations

In the context of the current thesis, the hygrothermal performance of PCLP walls of mass production buildings (series 1-464 and 111-121) from the 1960s to the 1990s was included to the research selection.

The general need for renovation and the structural strength (structural stability, loadbearing, corrosion), structural and architectural design of the buildings were not analysed in this work.

Life cycle analysis and recycling of materials with cost-efficiency measures are described in the form and extent needed to describe the hygrothermal performance of the studied and developed structures.

The designed prefabricated timber frame insulation elements are a part of ventilated facades of airtight external walls. This means that the wind-driven rain (WDR) load does not influence the hygrothermal performance and material selection like in case of ETICS. The dominating hygrothermal loads are indoor climate and outdoor air temperature, relative humidity, radiation, minor WDR through the facade boarding and IMC of the materials and structures.

The common and frequently used on the regional market materials for prefabricated insulation elements – wooden materials (pine and spruce), mineral wool (MW), cellulose wool (CW), wind barriers made of MW or cement-, gypsum- or wood-based materials and sheathing membranes – were included into the range of the analysed sets and combinations of the studied structures.

1.3 New knowledge and practical application

The results of the research provide the following new knowledge:

- It was shown that to guarantee moisture safety, the building envelope of the highly insulated and nZEB needs very careful hygrothermal design and thorough consideration of material properties;
- The determination of the critical IMC ($w \leq 110$ kg/m^3) of the PCLP wall before the installation of the additional insulation elements on top of the original envelope is vital to avoid mould and condensation problems;
- The dry-out capability of the additionally insulated structures varies in a large scale (from 6 to 24 months), depending mainly on the properties of the materials but also on the adherence to the quality and commission requirements;
- The installation of the timber frame insulation elements is possible with almost all common on the market products, but the most favourable set has to be calculated and designed always according to the individual condition of each building.

The new knowledge acquired can be implemented into practical applications as follows:

- The models of hygrothermal analysis used are calibrated and justified with measurements. Therefore, these models might contribute as a tool and basis for future projects groundwork;
- The diagrams presented in papers II, III and V give an overview for designers and contractors about the moisture loads and impact of precipitation on the dry-out capability. This information is valuable also for on-site works planned in rainy seasons;
- The commissioning of hygrothermal performance and measures described in paper V can be taken as a basis for standardisation of moisture safety inspection and could be included as a mandatory part to building contracting;
- The figures in paper IV and tables providing comparisons in paper VI can be considered as a baseline for preparing a tool for professionals for the preliminary design phase of deep energy renovation to evaluate hygrothermal boundaries and for cost-efficiency estimations of selected sets for further discussion with contractors and other contributors;
- Deep energy renovation of an existing apartment building to nZEB energy performance level was demonstrated by using prefabricated timber frame insulation elements.

2 Overview and description of renovation concepts

2.1 Background

Prefabrication of buildings has been one of the methods to improve the quality and to increase the effectiveness of construction for many decades. Development of concrete large panel systems started already before World War II and the growth remained intensive in the post-war period while housing shortage, recovering economy, urbanisation and consumers' ambitions set new challenges to the construction industry and real estate market.

Use of prefabricated concrete large panel (PCLP) construction technology for apartment buildings has been applied extensively in many countries since the 1960s (Hall and Vidén 2005, Lahdensivu 2012, Barański and Berkowski 2015). As more than 70% of the residential buildings in Europe are over 30 years old and about 35% are more than 50 years old (Balaras et al. 2005), a complete technical improvement of their condition has been receiving increasingly more attention.

In Estonia, the first PCLP building was erected in 1961 when the relevant production technology was imported from France. There are 264 000 dwellings in Estonia with a total net area of $66\,692 \cdot 10^3$ m^2 and about 65% of the inhabitants in Estonia live in apartment buildings (Statistics Estonia 2016). Nearly half of these buildings are built of PCLP elements where the thermal transmittance of the original (non-renovated) external envelope $U = 0.8$–1.5 W/(m^2·K), which is 5–10 times higher than what is considered reasonable today (RT I, 13.12.2018, RT I, 22.08.2019). See examples in Figure 2.1.

Figure 2.1 Examples of typical to Estonia PCLP apartment buildings, built in the 1960s–1970s (series 1-464, left) and 1980s–1990s (series 111-121, right). Photos from publications VI (left) and III (right).

The maximum designed service life of this type of buildings was 50 years, which is over for houses built in the 1960s and 1970s. Therefore, complex decisions have to be made and actions taken. Ilomets (2017) studied the renovation need and performance of envelopes of concrete apartment buildings in Estonia and showed that the corrosion propagation time of the original reinforced concrete facade exposed to severe wind driven rain (WDR) loads before renovation is approximately 3–6 years after the carbonation depth has reached the reinforcement. Corrosion due to the carbonisation of concrete facades is a major problem and cause of the need for renovation. Because of serious thermal bridges and high indoor humidity loads the calculated risk for surface condensation is 51% for concrete apartment buildings and the probability of mould growth is 54%. Therefore, an additional external thermal insulation together with the improvement of ventilation is advised in order to eliminate critical thermal bridges and to stop degradation mechanisms.

The environmental impact of new residential buildings is negligible compared to the impact of the existing residential building stock in the EU but the replacement rate of the existing stock is only 1–2% per year. Therefore, the existing buildings will still make up most of the housing stock in the coming decades. This means that accelerating the renovation rate is highly needed. Implementing a long-term renovation strategy requires more efficient solutions than we can see today (e.g. higher performance, unified solutions in mass production, lower cost). If the construction work is executed on the building site (i.e. most of production is given by tailored manual work), the price will remain high as the demand will gradually increase. Ways have been found for mass production, scale effect is achieved and with that the final prices are going down (van Oorschot et al. 2016, Österbring et al. 2019).

Renovation needs and the performance of the external envelope have been recently well studied (Hradil et al. 2014, Ilomets 2017). Research of current technical conditions of the Estonian old concrete panel housing stock refers to satisfactory conditions in terms of load-bearing, but highlights insufficient energy performance, poor indoor climate and hygrothermal performance of the building envelope, and also shows that it is reasonable to reduce the thermal transmittance of large panel apartment buildings' envelope down to $U = 0.15$ W/(m^2·K) but for that, ~300 mm thick insulation has to be installed on the external envelope (Kuusk and Kalamees 2015).

Several problems related to the hygrothermal performance of structures need to be solved in the design and construction process of building envelopes with thicker thermal insulation and lower thermal transmittance to guarantee the moisture safety of the building envelope (Hagentoft and Harderup 1996, Toratti et al. 2012, Gullbrekken et al. 2015). Studies have shown that in addition to energy performance, it is necessary to pay attention to the moisture safety measures in the design of additional insulation and construction of highly insulated buildings (Vinha 2007, Lattke et al. 2009). It is common engineering practice that the thermal transmittance of the building envelope is regulated by the thickness of the insulation layer without large changes in other materials. Vinha et al. (2013) and Fedorik et al. (2015) pointed out that decreasing thermal transmittance without changing other properties of the building envelope could increase the risk of mould growth in highly insulated building envelopes.

These aspects have been reported to be crucial in many countries with cold and humid climate. In Sweden thicker thermal insulation was found to increase moisture and mould damage (Harderup and Arfvidsson 2013). In addition, renovation with additional attic insulation has led to low temperatures in the attic space and hence a higher humidity (Hagentoft and Kalagasidis 2010). Vinha et al. (2013) showed that stricter requirements in Finland for the energy efficiency and increased thickness of thermal insulation will lead both to changes in building technology and in structures and may become a source of substantial moisture-related problems in building envelopes in the far future as a result of climate change. Langmans et al. (2012) analysed highly insulated timber frame walls with an exterior air barrier in laboratory conditions in Belgium and showed an increased moisture flow at the upper part of the walls driven by buoyancy forces. Bumanis and Pugovics (2019) analysed the low energy facade retrofitting solution in Latvia and reported higher humidity loads behind the outer layers of the cladding and some fungal growth on the corner areas with thermal bridges.

A large number of moisture-related building problems such as mould growth and chemical emissions from decomposed material subjected to high moisture levels have occurred during the last few years with adverse effects on health, building costs and confidence in the building industry (Mjörnell et al. 2012). Longer constructional moisture dry-out time and wettability of materials weaken the hygrothermal condition of the entire building envelope. Therefore, it is needed to pay special attention to hygrothermal performance and moisture safety in the design and building processes of highly insulated buildings.

In the present thesis it is shown that in a cold climate, the risk of mould growth increases on the inner surface of the water vapour resistant layer (e.g. wind barrier) because of the higher relative humidity (*RH*) caused by the lower temperature. Also, I show that under cold climate conditions external walls of large concrete panel apartment buildings with prefabricated timber frame insulation elements have the most critical to mould growth area between the original wall and the water vapour resistant layer (e.g. air- and vapour barrier) of the prefabricated element, caused by the initial moisture content of the original wall.

2.2 Motivation

Because of the rapidly growing energy demand and emergent markets, the energy efficiency and improvement of overall conditions of residential buildings are receiving increasingly more attention. These processes are supported by global agreements and European Union (EU) legislation with concurrent regional and local activities. The EU has adopted an ambitious vision for the reduction of GHG emissions and climate impact of the buildings stock where the decrease of energy use plays an important role. The Energy Performance of Buildings Directive (EPBD) (2010/31/EU) requires that all new buildings should be nearly zero energy buildings (nZEB) from the end of 2020. Improvement of the energy performance of new buildings is not enough to achieve energy performance targets because the replacement rate of buildings is only a few per cent. The revised EPBD (2018) pays more attention to the renovation of buildings than before. The European Commission recommends (2019/786/EU) that Member States shall establish a long-term strategy to support the renovation of the national stock of residential and non-residential buildings, both public and private, into a highly energy efficient and decarbonised building stock by 2050, facilitating the cost-effective transformation of existing buildings into nZEB.

Current renovation rates are not high enough to achieve decarbonisation targets timely (Sandberg et al. 2014, Filippidou et al. 2017) and financial support for renovation is needed (Baek and Park 2012, Kuusk and Kalamees 2016, Bjørneboe et al. 2018, Ebrahimigharehbaghi et al. 2019). In Estonia it took about two years to reach 30 renovation grant applications per month (Kuusk et al. 2019, RT I, 09.04.2019). Nevertheless, just demanding more renovation and offering financial support are not enough for effective results. The tripled volume of renovation created problems such as shortage of contractors, construction workers and construction materials and a 20% increase of construction costs in a relatively short period of time. These developments confirm the urgent need for more effective technologies and a new approach.

Construction methods based on fieldwork, consisting of long-lasting manual work and use of scaffolding, have been on the market for ages. However, under the unescapably changing weather conditions, varying knowledge and quality of the installation, the results obtained are not always in agreement with today's expectations (Pereira et al. 2018, Błaszczyński and Sielicki 2019). Installation of an external thermal insulation system (ETICS) or timber (or other similar) frames manually to the external envelope, filled in between with insulation layers and covered by wind and weather protective facade layers, has been a common method for the refurbishment as well as for new buildings and building extensions. However, it involves risks and failures could happen (Kalamees et al. 2008, Geving 2017, Nelson 2017, Rode et al. 2017).

Therefore, market participants are in search of alternatives to improve the existing building stock by means of innovation and efficient prefabrication coupled with lesser disturbance to the residents of the buildings.

2.3 Importance of quality assurance and commissioning

To reduce energy use and CO_2 emissions of historic dwellings, Moran et al. (2014) used thermal transmittance for roof U_{roof} = 0.14 W/(m²·K) in England and Leardini et al. (2015) in New Zealand used U_{roof} = 0.17 W/(m²·K). Kalamees et al. (2016) showed that for nZEB renovation the thermal transmittance of walls should decrease to U_{wall} = 0.11–0.47 W/(m²·K) depending on the climate and national requirements in European countries.

Design and construction of highly insulated building envelopes is a demanding process where hygrothermal performance plays a critical role in order to reach justifiable outcomes. Standardisation, quality assurance and commissioning procedures become more and more important when designing, constructing new and renovating existing buildings to energy efficient ones. The quality and firmness of the product are guaranteed through standardisation of procedures. For all parties in the supply chain the effect of standardisation may be relatively insignificant but in the construction industry it is the main principle to guarantee sustainable, healthy and effective (i.e. competitive) outcomes. In energy performance and deep renovation, it should be interpreted as confidence to owners in savings achievement, reduction of due diligence costs and conformity to high durability irrespective of contractor or complexity of the project.

An industry standard (ByggaF 2013) was developed in Sweden to minimise moisture-related problems that incur negative consequences for health, increase costs for rebuilding and cause lost confidence in the building industry (Mjörnell et al. 2012). Moisture safety methods also exist in other Nordic countries (Geving 2017, Kosteudenhallinta.fi 2019, Sisäilmayhdistys ry 2019).

Based on the EU Construction Products Regulation (CPR) (2011/305/EU), manufacturers have to draw up technical documentation describing all the relevant elements related to the required system of assessment and verification of constancy of performance. The European Technical Approval Guidelines (ETAG 023 2006, ETAG 007 2013) can also be used for assessments of construction products in line with the requirements. The renovation of buildings is not a fully standardised process where one building component is suitable for many buildings because of the differences in building typology and climatic conditions. Quality assurance systems for the retrofitting process have been developed (SQUARE 2008, Sinfonia 2019, Wallenten and Mjörnell 2019) to ensure that the most efficient measures are chosen and a high level of integrated energy and indoor environmental performance is maintained throughout building operations.

We see that several single quality assurance and commissioning systems with multiform scopes exist. Nevertheless, no integrated system with accent on moisture safety in deep energy and nZEB renovation with prefabricated insulation elements is widely used yet. Even though we can find good examples (e.g. from Nordic countries), the implementation of these methods needs performance criteria for requirements and for local adaption.

2.4 Concepts of the different prefabricated insulation systems

An efficient way to achieve the purpose of deep energy renovation on a larger scale is to apply an integrated design process and use prefabricated renovation elements. This is one of the ways to obtain high energy efficiency and quality both in production and installation processes. By using prefabricated insulation elements it is possible to increase quantities and the quality when renovating buildings (Veld 2015). Cost-effectiveness and advanced energy-efficient retrofit strategies that create added value for the existing building stock have been investigated in several projects, which have proved the viability of the new retrofitting solutions (Heim et al. 2014, Katsifaraki et al. 2014, Tellado et al. 2019).

The International Energy Agency's Energy in Buildings and Communities Programme (IEA ECBCS) Annex 50 'Prefabricated Systems for Low Energy Renovation of Residential Buildings' in 2006–2011 (Miloni et al. 2011) concentrated on typical apartment buildings and was focused on energy efficiency and comfort in buildings, optimisation of construction and cost efficiency of prefabrication. The case study buildings renovated in the framework of that programme were six demonstration buildings in Austria, Netherlands and Switzerland (see Figure 2.2). It was pointed out that the definition of the tolerance space needed between a building and modules and the accurate mounting of the module support brackets around the building are important to consider.

Figure 2.2 IEA ECBCS Annex 50 prefab elements production for the case study building in Switzerland (left) and assembly of the elements in the Austrian case study building (right) (Miloni et al. 2011).

In 2008–2009 researchers from Finland worked in cooperation with German and Norwegian partners to realise the research project titled 'Timber Based Element Systems for Improving the Energy Efficiency of the Building Envelope (TES Energy Facade)'. The goal of the project was to develop a facade renovation method (TES method) based on large-scale, timber-based elements for the substantial improvement of the energy efficiency of renovated buildings that would be applicable throughout Europe. The TES Energy Facade defined the basic principles for the energy modernisation of the building envelope using prefabricated large-sized timber frame elements. The basis for the use of prefabricated retrofit building elements is a frictionless digital workflow from survey, planning, off-site production and on-site mounting based on a precise initial three-dimensional (3D) measurement (see Figure 2.3). The Technical Report of the TES Energy Facade project (Lattke et al. 2009) pointed out the importance of moisture control and an individual moisture simulation of the chosen structures by dynamic simulations but did not present strict numeric limits to the IMC. It was noted that the TES element has to be diffusion open to the outside, with a low water vapour resistance (0.3 m ≤ S_d ≤ 4 m) on the outside of the element and water vapour diffusion resistance S_d at least six times higher on the inside of the element. Also, the TES element joints have to be sealed for airtightness to ensure the required moisture performance (Loebus et al. 2014).

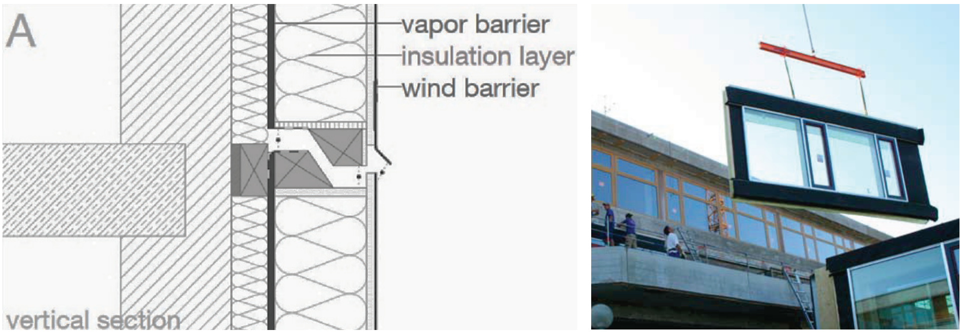


Figure 2.3 Vertical section of the principal design of a TES element (left) (Loebus et al. 2014). Mounting of TES elements in Finland (right) (Lattke et al. 2009).

In Sweden the technology procurement 'Technology Procurement of Rational Insulation of External Walls and Facades of Existing Apartment Buildings' (in Swedish: *'Teknikupphandling: Rationell isolering av klimatskärmen på befintliga flerbostadshus', TURIK*) (Mjörnell 2011) was started because there was a need for the development of rational solutions for improved energy performance of the building envelope, primarily walls, designed for energy efficiency of existing buildings. According to the requirements of the project, analysis of the hygrothermal performance of all systems was performed. The report stated that the solutions should be produced and assembled in a rational way, be cost-effective, have a low environmental impact during their life cycle and be persistent, which means maintenance requirements and low risk of damage. See Figure 2.4 for examples of the research made.

Figure 2.4 Testing of facade details in the project of insulation and technology procurement in laboratory (left) and on the plastered facade in Sweden (right) (Mjörnell 2011).

The EU Horizon2020 project E2ReBuild (Heim et al. 2014) in 2011–2014 with many partners from all over the EU was aimed to investigate, promote and demonstrate cost-effective and advanced energy efficient retrofit strategies that create added value for existing apartment buildings and endorse end-users to stay and build a dynamic society, to establish and demonstrate sustainable renovation solutions that will greatly reduce the energy use, to create a holistic industrialised process that minimises technical and social disturbance for tenants and facilitates energy efficient operation and use of the buildings including encouraging energy efficient behaviour. The E2ReBuild demonstration projects made use of results from research on innovative and sustainable renovation solutions. Specifically, the focus was on industrialised manufacturing of facade elements and standardised retrofit measures with a high replication potential. See examples in Figure 2.5.

Figure 2.5 E2ReBuild demonstration project in Oulu, Finland. New insulation installed on facades, roof and ground floor slab and new technical appliances (Heim et al. 2014).

The RetroKit project (Katsifaraki et al. 2014) in 2012–2016 developed and demonstrated multifunctional, modular, low cost and easy to install prefabricated modules, integrating efficient energy use systems and renewable energy sources for systemic retrofitting of residential buildings.

The MeeFS project in 2012–2016, Multifunctional Energy Efficient Facade System for Building Retrofitting (MEEFS 2016), was aimed to develop an energy efficient integrated system composed by an innovative concept, built on composite materials, and advanced multifunctional panels with technological modules integrated in the facade for building envelope retrofitting. Innovative facade concept for retrofitting was based on new industrialised constructive system integrating advanced multifunctional panels, technological modules and installations, allowing personalised configurations for each facade typology, orientation and local climate conditions, always using standardised panels and technological modules. It was meant to be cost effective in service life, with low maintenance, easy to be industrialised and assembled, made of composite materials.

The Ri.Fa.Re. (in Italian: *Ristrutturare con Facciate pRefabbicate*) project in Italy in 2013–2017 (Malacarne et al. 2016), managed by the Fraunhofer Innovation Engineering Centre in Bolzano in collaboration with five local companies, concentrated on timber-based solutions that had to be lightweight and suitable for varying climatic conditions, customisable but with a low unit cost typical of mass production, prefabricated and quick to be installed on site, optimised with a standardised production and construction process. One of the methods was the dynamic simulation of moisture transfer across building components allowing identification of possible critical areas along the Ri.Fa.Re. timber-based solution and proper placement of protecting membranes such as vapour retarders, vapour barriers and waterproofing membranes (see Figure 2.6).

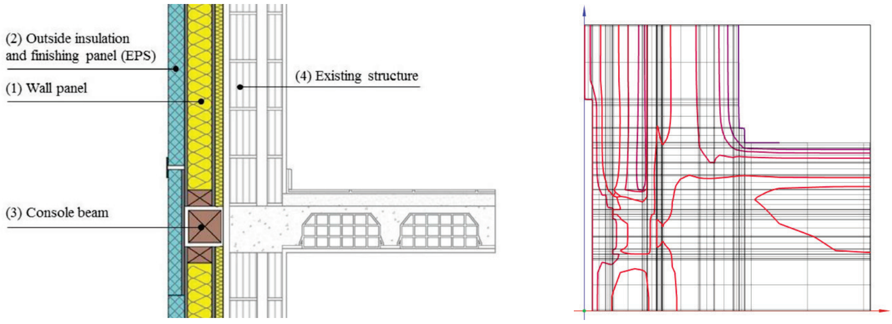


Figure 2.6 The Ri.Fa.Re. timber-based solution (left) and dynamic calculation of relative humidity in the elements (right) (Malacarne et al. 2016).

The objective of the project iNSPiRe (Ochs et al. 2015) was to tackle the problem of high energy consumption by producing systemic renovation packages that can be applied to residential and tertiary buildings. In that project the development, testing and modelling of a timber frame facade with integrated mechanical ventilation with heat recovery and a micro heat pump were presented and tested in three demo buildings.

The EU Horizon2020 project BERTIM (2015–2019) developed a standardised product for the wood industry for energy efficient renovation. The targets of the BERTIM methodology are buildings in need of improved thermal performance of their envelopes and building systems (Tellado et al. 2019). The proposed holistic renovation process includes many outputs, e.g. building data gathering (building materials, systems, structure and facade geometry obtained by means of laser scanner, total station or photogrammetry), creation of the Building Information Modelling (BIM) tool to calculate energy savings, costs and configuration of timber modules production. BERTIM panels became suitable for facade refurbishment from the technical point of view, but there was room for the improvement of the whole process by means of industrialisation and automation of manufacturing and installation processes (Lasarte et al. 2017). See examples in Figure 2.7.

Figure 2.7 Integrated appliances in the elements (left). Installation of elements in the BERTIM project (right) (Lasarte et al. 2017).

The EU Horizon2020 project 'MORE-CONNECT' was realised in 2015–2019 to develop energy efficiency, hygrothermal performance and aesthetics of buildings and demonstrate technologies of prefabricated modular renovation elements, including the prefab integration of multifunctional components, e.g. for climate control (Veld 2015) (see Figure 2.8). The main objectives in this project in addition to energy efficiency and savings were reduction of renovation time on the building site with lesser disturbance to inhabitants, minimising construction failures and 'one-stop-shop' scheme where the end-user will deal with only one party, responsible for the total renovation.

Figure 2.8 Modular pipe installation prototyping in the Czech Republic (left) and in Estonia (right) in the MORE-CONNECT project (2016).

Within the Nordic project Nordic Built Concept (Sandberg et al. 2016) in 2016 for the renovation and upgrading of residential buildings simulation of moisture cases in six different wall constructions of the modular system was performed and results showed no sign of problems with condensation.

Also, the EU Horizon2020 project P2Endure (2016–2020) promotes evidence-based innovative solutions for deep renovation of building envelopes and technical systems based on prefabricated Plug-and-Play (PnP) systems in combination with on-site robotic 3D-printing and BIM. P2Endure aims to increase the scale and level of the adoption of innovative solutions for deep renovation through innovative combinations, processes and supporting information communication tools (Sebastian et al. 2018).

The recent research on technical, financial and social barriers and challenges in deep renovation of buildings points out that the main barriers are not related to specific technical problems but are due to insufficient deep renovation and nZEB knowledge, in case of both building owners (i.e. awareness and commitment) and designers (i.e. managing properly the design and construction process in order to guarantee the expected performance and targets set) (D'Oca et al. 2018). Even if retrofit to the low energy building level were economically viable, the investment capability of apartment owner associations could be insufficient for the necessary investments to achieve low-energy-building energy performance (Kuusk and Kalamees 2016). In Estonia, the market value of the real estate outside of the attractive areas and cities, where still about 33% of the population lives (Statistics Estonia 2016), is usually low and being below the accepted limit to get the loan for financing (Hess and Tammaru 2019). Also, there are no notable rental companies and market in Estonia as about 82% of dwellings are privately owned and usually occupied by the owner. In that kind of situations, partial renovation could be one of the ways to move on (Femenías et al. 2018).

The literature review and described hereinbefore projects reveal that many development programmes have focused primarily on energy and cost-effectiveness with a commitment to develop implementation of prefabricated modules, elements and appliances for buildings deep renovation. We can see the importance of the preliminary stages of the project with the use of the state-of-the-art tools to collect and process data needed for design. Analyses of energy and cost-efficiency are an integral part not only for the end-user but also for production planning. The majority of the projects realised, besides the developing included also real-life renovation pilots with integrated appliances, proving the suitability of the use of prefabricated elements instead of conventional renovation solutions. Nevertheless, the methodology where the external core or even all layers of the envelope are removed and replaced with new prefabricated elements is not applicable in cases where the concrete core is the integral part of the loadbearing structure (like it is with pilot building type, studied in present thesis). However, most of the described projects have not analysed (or reported the results of) the hygrothermal performance associated with the original building envelope and its condition. Also, comparison of different materials and their properties in elements would be important to study. Therefore, the relevance to analyse and discuss these topics is significant.

3 Methods

The present thesis examines potential hygrothermal risks and their effect on prefabricated timber frame insulation elements used in the deep energy renovation of prefabricated concrete large panel (PCLP) apartment buildings in cold and humid climate conditions. The methods of the study are divided into five main phases of hygrothermal analysis, measurements, calculations and development. The methodology of the analyses made, and steps taken are marked in Table 3.1 as follows:

Quantitative analyses:
1 Measurements on building site
2 Measurements in lab, prototyping
3 Simulations, calculations

Qualitative analyses:
4 Visual evaluation on building site
5 Observations on building site, in factory
6 Workshops, meetings, interviews

Table 3.1 Description of the methodology used.

Analysis scope	Quantitative analyses			Qualitative analyses		
	1	2	3	4	5	6
A. Hygrothermal parameters influencing highly insulated timber frame structures			√			
B. Performance of the PCLP wall before renovation	√	√	√	√	√	
C. Development of prefabricated timber frame insulation elements		√	√	√	√	√
D. Performance of the PCLP wall after the renovation with prefabricated timber frame insulation elements	√		√	√	√	√
E. Material combinations and energy and cost of prefabricated timber frame insulation elements			√			√

Construction types studied are described in section 3.1, measurements and parameters in section 3.2, dynamic simulations and calculations in sections 3.5 and 3.7.

Visual evaluation on the building site consisted of metering and visual detection of the building's state, which was performed in the predesign, development and post-renovation stages.

Observations on the building site or in the factory were performed repeatedly after the start of construction works on site and during the production of timber frame elements at the factory.

Workshops and meetings were performed periodically in the development and construction stages, followed by interview sessions.

3.1 Construction types studied

3.1.1 Highly insulated timber frame structure

In this phase of study, a timber frame exterior wall (see Figure 3.1) with a ventilated facade and with different thermal transmittances (U 0.17, 0.14, 0.12, 0.10, 0.08 W/(m^2·K)) and several material combinations was analysed (see Table 3.2).

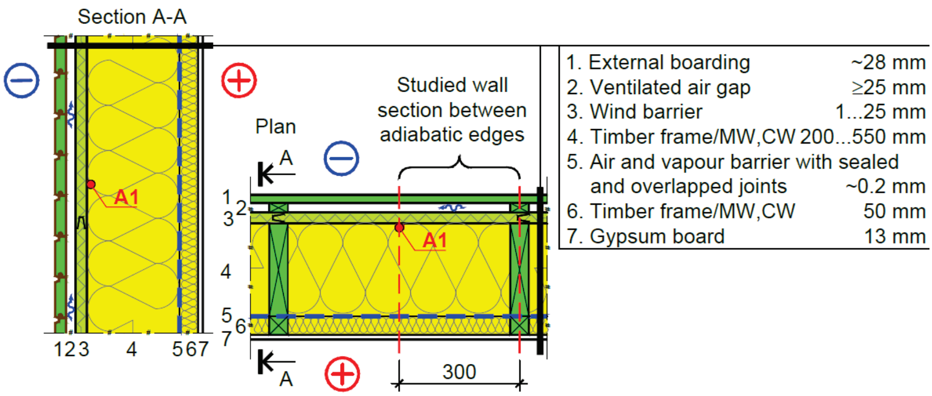


Figure 3.1 Studied timber frame exterior wall. Scale 1: 20. Reproduced from publication I.

In order to compare the hygrothermal indicators and to analyse their impact, thermal insulation materials (mineral wool (MW) and cellulose wool (CW)), air and vapour barrier materials (polyethylene (PE) foil, kraft paper processed with PE, bitumen paper) as well as wind barrier materials (wood fibreboard, MW wind barrier board, wind barrier gypsum board, strand board) were used in the structures in combination with each other. The exterior wall with thermal transmittance $U = 0.17$ W/(m^2·K), fulfilling the current energy performance requirements in Estonia (RT I, 13.12.2018), built of an unprocessed timber (not planed pine) frames, insulated with 200 mm + 50 mm MW, covered with 22 mm wood fibreboard as a wind barrier and with an air and vapour barrier (kraft paper), was used as a reference case for analysis of the timber frame structure with the criterion of mould index $M < 1$ in the most critical with regard to hygrothermal risks point A1 (see Figure 3.1).

3.1.2 PCLP wall of the pilot building for deep energy renovation with prefabricated timber frame insulation elements

A PCLP apartment building that had undergone a deep energy renovation with prefabricated timber frame insulation elements was selected as the pilot and main object of the research of the thesis. It is a 5-storey PCLP building with a total area of 4318 m^2. The building is located at the campus of Tallinn University of Technology at 5A Akadeemia tee, Tallinn, and serves as a dormitory for student families. It was constructed in 1986 and is analogous to mass production apartment buildings (series 111-121) from the 1960s to the 1990s representing the dominating in Estonia apartment building type of that period (Hess and Tammaru 2019).

The original PCLP wall with a thickness of 250 mm consists of two concrete sections and insulation layers (see Figure 3.4, Figure 3.5 and Figure 3.11, top): 60 mm exterior reinforced concrete slab + 70 mm wood-chip insulation layer + 50 mm phenolic foam insulation layer + 70 mm interior reinforced concrete slab. The original flat roof with a parapet (see Figure 3.4) is covered with bitumen felt and insulated with wood chip boards.

The thermal transmittance of the original envelope varies, being U = 0.9–1.1 W/(m^2·K). Depending on the building and its construction quality, dimensions and insulation materials may vary.

Figure 3.2 Facade details of the pilot building before renovation (2015).

Connections of the building envelope contain serious thermal bridges (see Figure 3.4 to Figure 3.6; insulation layers are highlighted in yellow (installed in PCLP factory) and green (installed in-situ) and concrete in light brown in Figure 3.4 and Figure 3.5). The measured temperature factor (f_{Rsi} < 0.80) was below the accepted limit (Kalamees 2006a, EN ISO 13788 2012). Because of apparent thermal bridges, mould growth on interior surfaces, especially in the corners of exterior walls, interior walls and intermediate floor, was observed in many apartments (see Figure 3.3 and Figure 3.6, middle).

Figure 3.3 Mould grows on the surface of the connection of the external wall, internal wall and intermediate floor of the pilot building (2015).

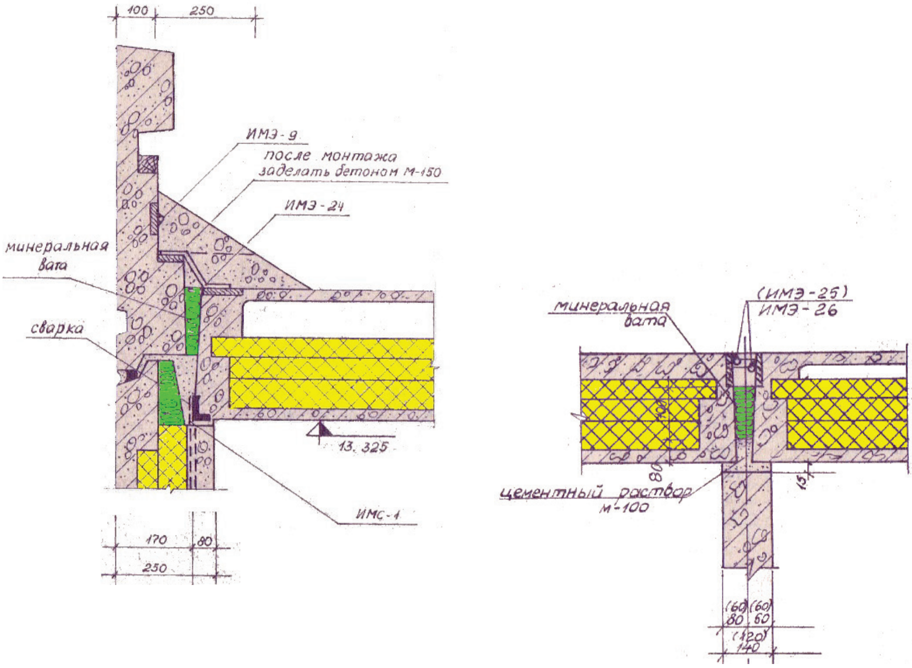


Figure 3.4 *Vertical sections of connections of the external wall and roof (left) and an internal wall and roof (right) of a PCLP building, series 111-121. Scale 1 : 20. (Based on original drawings from Estonian State Archives 1974). See Figure 3.6 (top) for references.*

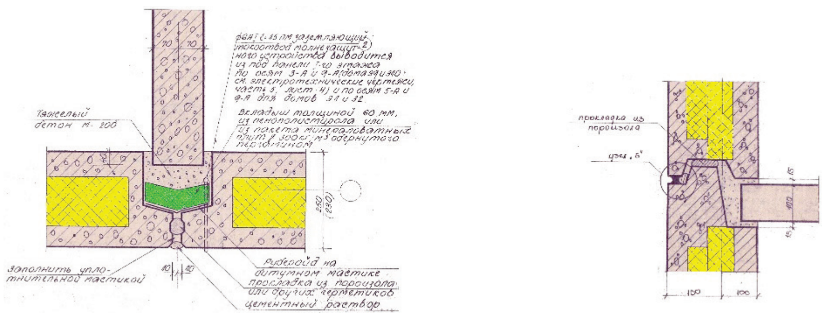


Figure 3.5 *Horizontal section of the connection of external and internal walls (left) and vertical section of an external wall and the intermediate floor (right) of a PCLP building, series 111-121. Scale 1 : 20. (Based on original drawings from Estonian State Archives 1974). See Figure 3.6 (top) for references.*

Figure 3.6 *Measurement areas (top) and thermal bridges on the external walls (middle and bottom) before the nZEB renovation and installation of prefabricated elements (2015). Adapted from publication IV.*

The building had problems typical to many other older buildings: high energy consumption, insufficient ventilation, overheating during winter, unsatisfactory thermal comfort. The fresh air inlet was initially designed through the slits around untightened wooden window frames and natural exhaust via the kitchen and sanitary rooms to the central shaft. The building had a one-pipe radiator heating system without thermostats, and the room temperature for the whole building was regulated by a heat substation depending on the outdoor temperature (Kuusk, Kalamees, and Pihelo 2016). The total delivered annual energy before renovation with indoor climate class (ICC) III (i.e. acceptable conditions, moderate level of expectation) was 276 kWh/(m^2·a), incl. 168 kWh/(m^2·a) for space heating and room airing, 59 kWh/(m^2·a) for domestic hot water (DHW) and 49 kWh/(m^2·a) for electricity (Hamburg et al. 2020).

3.2 Measurements and parameters used in studies

Measurements in different phases of the research and deep energy renovation process at different spots of the studied pilot PCLP apartment building were conducted and hourly logged data was collected as follows:

- From November 2015 to January 2016: thermography of the external envelope (outside) and apartments' critical areas (inside); analysis of pre-renovation state (see Figure 3.6);
- From November 2015 to April 2016: samples were drilled out from PCLP for the investigation of envelope dimensions, materials condition and properties: carbonisation depth, density, water vapour permeability (see Figure 3.7);
- From November 2015 to January 2017: external walls and apartments: hourly logged temperature (*t*), *RH* and heat flux (*q*); analysis of pre-renovation state (see Figure 3.8);
- From May 2017 to June 2017: moisture content in drilled-out from PCLP samples and lab measurements before and during the installation of prefabricated timber frame insulation elements;
- June 2017: installation of the sensors into the prefabricated timber frame elements at the factory of producer of timber-based elements and modules AS Matek (see Figure 3.9);
- From October 2017 to January 2018: measurements of air leakages from the building envelope (q_{50}); analysis of post-renovation state;
- March 2018: thermography of the external envelope (outside) and apartments critical areas (inside), analysis of post-renovation state;
- From July 2017 to November 2019: external walls and apartments; hourly logged *t*, *RH* and *q*; analysis of post-renovation state by using an online monitoring system; continuous analysis of post-renovation state (Figure 3.10).

Remark:
The underlined parameters were used in the present thesis for quantitative analyses; the other measured parameters were used in qualitative analyses or for commission purposes.

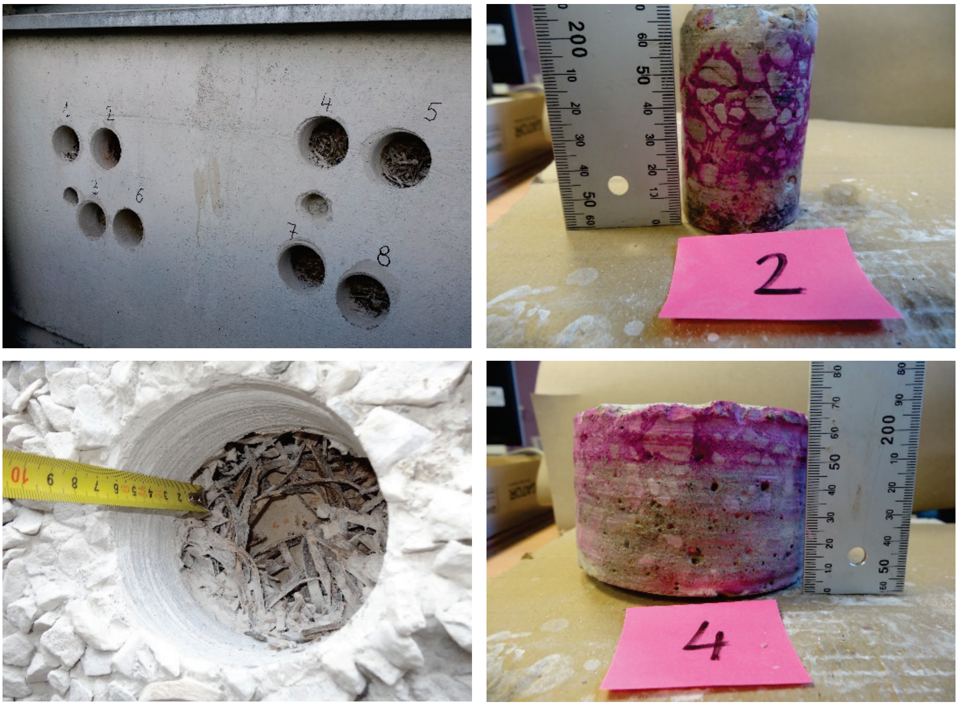


Figure 3.7 *Investigation of the facade (2015).*

Figure 3.8 *Measurements of the temperature, relative humidity and heat flux of the external wall (2015–2016).*

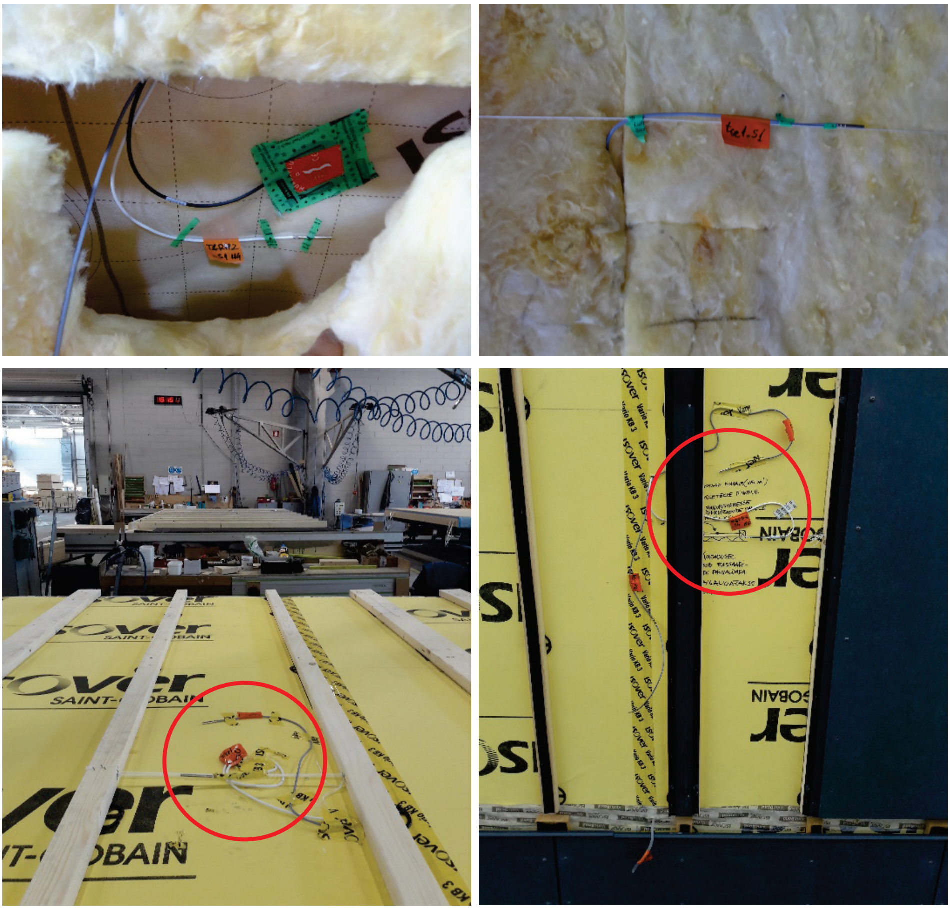


Figure 3.9 Installed sensors at the factory of AS Matek (left) and a view of the sensors after the installation of prefabricated insulation elements on the pilot building (right) (2017).

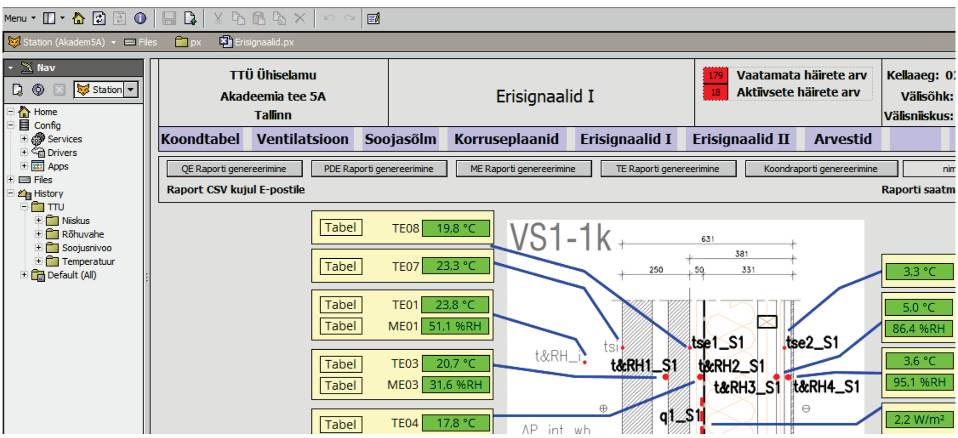


Figure 3.10 Overview of the online logging and monitoring system of the pilot building (2017).

Temperature and *RH* inside the wall were measured with a Ø 5×51 mm Rotronic HygroClip SC05 sensors (measurement range –30…+100 °C; 0–100% *RH* and accuracy ±0.3 °C, ±1.5% *RH*).

Air and surface temperatures were measured with HOBO TMC6-HD *t*/*RH* 2 external channel data loggers U12-013 (measurement range –20...+70 °C, accuracy ±0.35 °C).

Thermal transmittance was measured with a heat flux plate by using Hukseflux HFP01 (∅ 80 mm) and HFP03 (∅ 172 mm) sensors (measurement range ±2000 W/m^2, accuracy ±6%). See Figure 3.11 for the location of temperature and *RH* sensors and heat flux plates on the pilot building external walls.

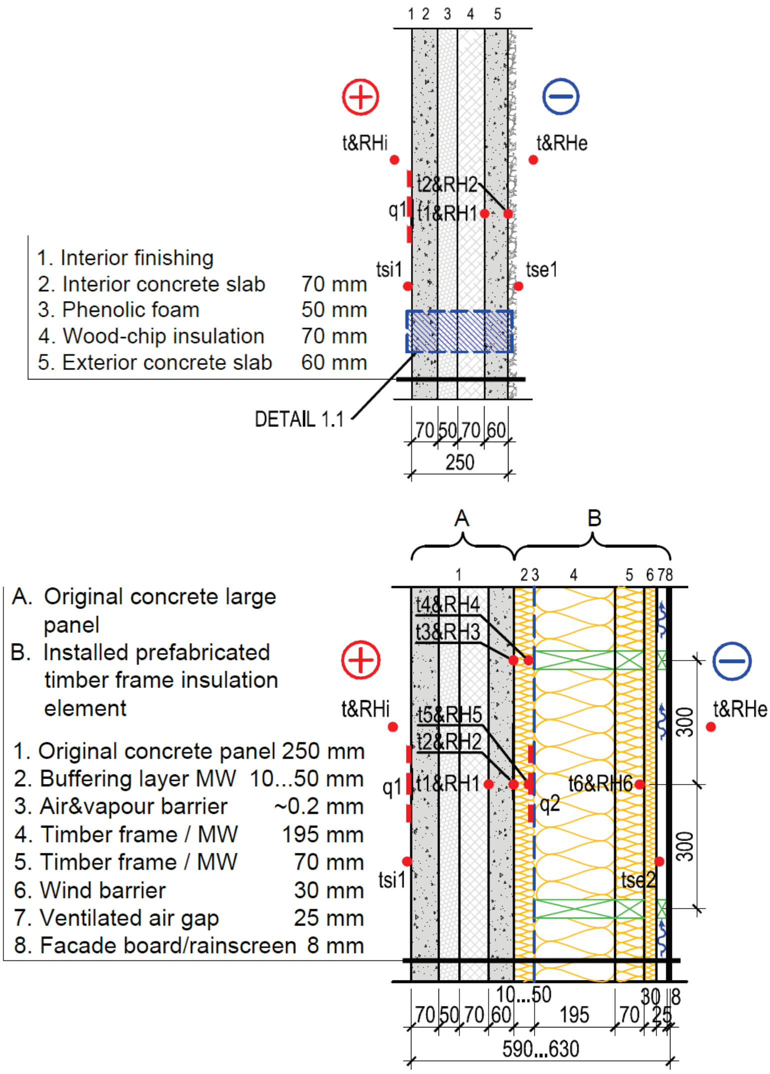


Figure 3.11 Measurement and calculation points of the PCLP wall before (vertical section, top) and after the installation of prefabricated insulation elements (horizontal section, bottom). Scale 1 : 20. Based on figures from publications II (top) and III (bottom).

Temperature factor f_{Rsi} was calculated on the basis of measured temperatures (t_i, t_{si}, t_e) of the envelope and on the relevant standard (EN ISO 13788 2012) according to Equation (1):

$$f_{R_{\mathrm{si}}} = \frac{t_{\mathrm{si}} - t_{\mathrm{e}}}{t_{\mathrm{i}} - t_{\mathrm{e}}} \tag{1}$$

where t_{si} is the interior surface temperature, °C; t_e is the outdoor air temperature, °C; t_i is the indoor air temperature, °C.

Air leakage q_{50} ($m^3/(h \cdot m^2)$) of the building envelope was measured by using Minneapolis BlowerDoor fan pressurisation equipment according to the ISO standard (EN ISO 9972 2015) together with the identification of air leakage and thermal bridge places with thermography by using an FLIR E302 thermal camera (measurement range –20...+500 °C, sensitivity 0.10 °C, accuracy ±2 °C and ±2%).

During the renovation, test samples from different parts of the PCLP walls were drilled out and taken to the lab for testing. According to the ISO standard (ISO 1920-5:2004), samples were weighed promptly and measured, then dried (dehydrated) in an oven in the lab. By using the mass difference, the moisture content (MC) of the material (*w*; *u*) was consequently calculated.

3.3 Climate conditions

The following parameters were used for outdoor climate in the current study:

- Air temperature, °C;
- Relative humidity, %;
- Rain flux density on a horizontal plane, $l/(m^2 \cdot h)$;
- Wind velocity, m/s;
- Wind direction, deg;
- Direct solar radiation, W/m^2;
- Diffuse solar radiation, W/m^2.

According to the Köppen-Geiger climate classification (Kottek et al. 2006), Estonia belongs to cold (continental) humid climate with warm summers (DfB). The outdoor climate data are based on Estonian long-term outdoor climate observations with 1-hour step for 1970–2019 from the closest to the pilot building weather station located in the western part of Tallinn (59°26′N, 24°45′E), where in 1981–2010 as an average of the year, t_e = 5.9 °C, RH_e = 81%, precipitation 704 mm, wind speed 3.5 m/s and annual sunshine 1826 hours (Jaagus et al. 2013).

In the assessment of hygrothermal risks, the hourly data of the moisture reference year (MRY), critical to mould growth and water vapour condensation in Estonia, was applied to outdoor climate (Kalamees and Vinha 2004).

Indoor climate measurements from Estonian dwellings (Kalamees 2006b, Kalamees et al. 2011, Arumägi et al. 2015) were used to determine critical indoor hygrothermal conditions.

For simulations, the following conditions were used: average indoor temperature, which is dependent on the outdoor temperature and indoor moisture excess $2 \leq \Delta v \leq 6$ g/m^3, representing dwellings with a high humidity load and high occupancy (indoor humidity class 3) according to the national annex of standard (EN 15026 2007), see Figure 3.12.

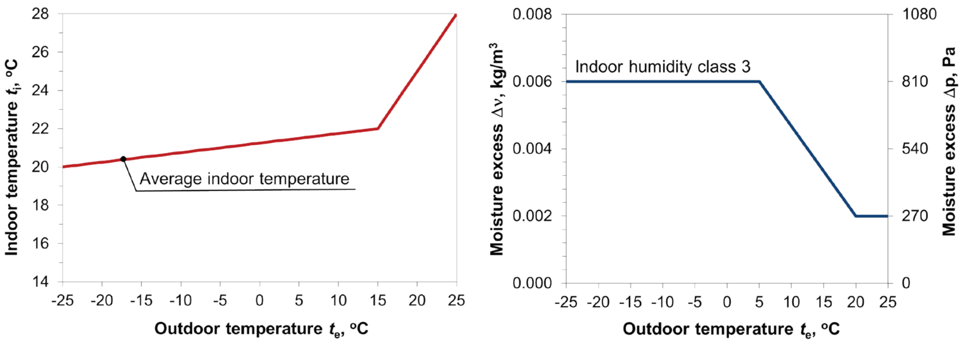


Figure 3.12 Dependence of indoor temperature (left) and design value of moisture excess (right) on the outdoor temperature. Reproduced from publication I.

The impact of wind-driven rain (WDR) was taken into account in this study according to the standard (EN ISO 15927-3 2009). Equations (2)–(4) characterise the calculation model of WDR to the vertical wall surface:

$$I_{\mathrm{WA}} = I_{\mathrm{A}} \cdot C_{\mathrm{R}} \cdot C_{\mathrm{T}} \cdot O \cdot W \tag{2}$$

$$I_{\mathrm{A}} = \frac{2}{9} \frac{\sum v \cdot r^{8/9} \cdot \cos\left(D - \theta\right)}{N} \tag{3}$$

$$C_{\mathrm{R}}\left(z\right) = K_{\mathrm{R}} \cdot \ln\left(z/z_0\right) \tag{4}$$

where I_{WA} is wall annual index (l/m^2), I_A is airfield annual index (l/m^2), C_R is roughness coefficient, C_T is topography coefficient, O is obstruction factor, W is wall factor, v is hourly mean wind speed (m/s), r is hourly rainfall total (mm), D is hourly mean wind direction relative to north (deg), θ is wall orientation relative to north (deg), N is the number of years with available data, K_R is terrain factor, z is height above ground (m), z_0 is roughness length (m).

In the calculations of this research, variables and coefficients were used as follows: $K_R = 0.24$ (urban areas, terrain category IV), $z = 16$, $z_0 = 1$ (terrain category IV), $C_T = 1$ (no upwind slope), $O = 0.3$ (distance of obstruction from wall 8–15 m), $W = 0.5$ (wall factor for buildings with a flat roof, for top 2.5 m), $\theta = 225°$ for SW, $N = 43$. The other variables (*v, r, D*) were from local climate hourly data from the years 1970–2012.

In Estonia, the moisture load to wall surfaces caused by WDR is the highest through October to December and in January, generated by the predominant wind from the south-west (SW) direction (Jaagus and Kull 2011). Our calculations with climate data from the period 1970–2012 are in agreement with this (see Figure 3.13).

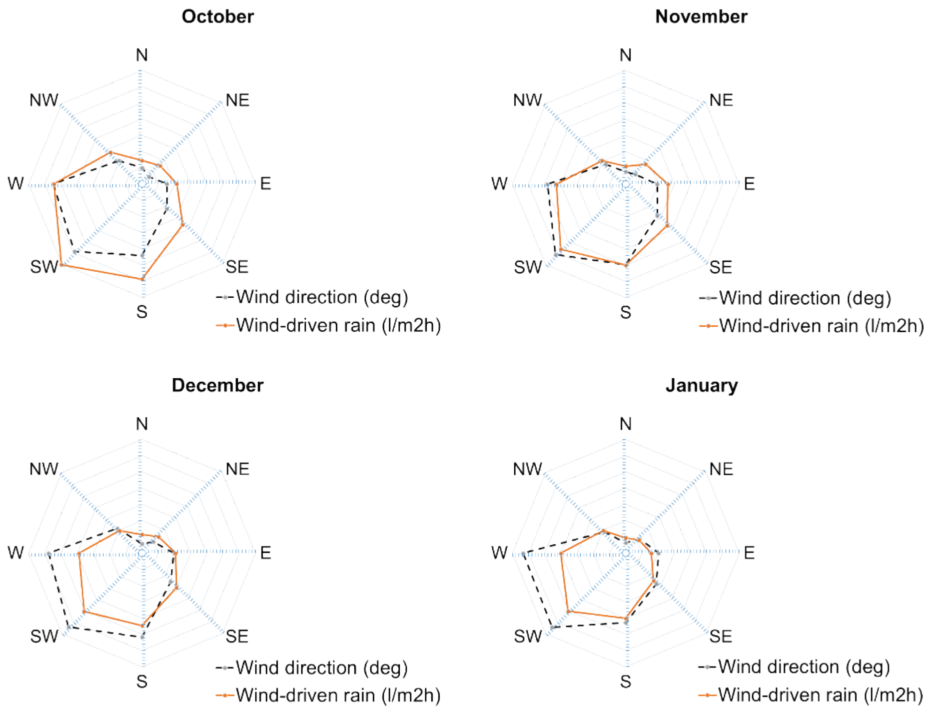


Figure 3.13 Diagram of prevalent directions of wind and WDR in the seasons with the highest moisture content (autumn–winter) of the studied period (1970–2012). Reproduced from publication II.

3.4 Materials

Materials used in the different phases of the research of the hygrothermal performance of the insulated timber frame structure and PCLP wall before and after the renovation are described in Table 3.2.

Table 3.2 Properties of materials in structures studied.

Material	Thermal conductivity λ, W/(m·K)	Moisture content w, kg/m³		Water vapour resistance factor μ, -	Density ρ, kg/m³	Water absorption coefficient A_w, kg/(m²·s^0.5)
RH	83%	83%	97%	83%		
General building materials						
Concrete* A	1.500	86.0	134	41.0	2320	0.0200
Gypsum board A	0.210	8.60	17.7	6.90	574	0.0761
Phenolic foam insulation* A	0.064	0.54	0.98	2.85	30	0.0010
OSB A	0.130	110	183	165	646	0.0113
Timber (pine) A	0.130	108	185	40.0	450	0.0155
Wood chip insulation* A	0.140	21.0	32.0	3.80	500	0.0089
Wind barriers						
Fibre cement board B	0.263	19.2	56.5	17.5	1350	0.0569
MW wind barrier B	0.031	0.96	3.30	1.80	104	1E-06
Wind barrier gypsum board A	0.190	11.5	23.8	7.90	774	0.0760
Wind barrier membrane (S_d = 0.015 m) B	0.120			14.9	247	0.0010
Wood fibre board A	0.050	40.0	75.0	5.00	270	0.0054
Insulation materials						
CW insulation A	0.049	6.80	13.0	1.40	37	0.0950
CW insulation A	0.045	11.0	21.0	1.50	70	0.0650
MW insulation B	0.035	0.80	2.40	1.20	22	1E-06
MW insulation B	0.037	0.80	2.40	1.20	20	1E-06
Air and vapour barriers						
Air and vapour barrier (0.2 m ≤ S_d ≤ 5 m) B	0.230			800	450	0.0001
Bitumen paper A A	0.120			90	840	0.0010
Bitumen paper B A	0.120			120	940	0.0010
Kraft paper A A	0.120			1150	756	0.0010
Kraft paper B A	0.120			3880	940	0.0010
Kraft paper C A	0.120			4500	956	0.0010
PE-foil A	0.400			89000	980	1E-06

* Materials in the PCLP original wall of the pilot building
A Material properties adjusted with lab tests and/or literature data
B Material properties adjusted with data from the material producer

3.5 Modelling

3.5.1 Simulation software

The validated dynamic simulation program Delphin (Grunewald 1997, Nicolai 2008) was used in this study for hygrothermal modelling. Delphin is a simulation program for coupled heat, moisture and matter transport in porous building materials. It is used for different applications, e.g. calculation of mould growth risks with consideration of climate impacts, structure conditions and materials modelling. The moisture mass balance is expressed as:

$$\frac{\partial}{\partial t}\rho_{\mathrm{REV}}^{\mathrm{m_{w+v+i}}} = -\frac{\partial}{\partial x}\left[j_{\mathrm{conv}}^{\mathrm{m_w}} + j_{\mathrm{conv}}^{\mathrm{m_v}} + j_{\mathrm{diff}}^{\mathrm{m_v}} \right] + \sigma_{\mathrm{REV}}^{\mathrm{m_{w+v+i}}} \tag{5}$$

where $\rho_{\mathrm{REV}}^{\mathrm{m_{w+v+i}}}$ is moisture density in reference volume (liquid water + vapour + ice) (kg/m^3), $\sigma_{\mathrm{REV}}^{\mathrm{m_{w+v+i}}}$ is moisture sources/sinks in reference volume (kg/m^3·s), j_{conv} is convective flux (kg/m^2·s), j_{diff} is diffusive flux (kg/m^2·s), m is mass, v is vapour, w is water, i is ice. The energy balance is expressed as:

$$\frac{\partial}{\partial t}\rho_{\mathrm{REV}}^{\mathrm{U}} = -\frac{\partial}{\partial x}\left[j_{\mathrm{diff}}^{\mathrm{Q}} + u_{\mathrm{l}} \cdot j_{\mathrm{conv}}^{\mathrm{m_l}} + u_{\mathrm{g}} \cdot j_{\mathrm{conv}}^{\mathrm{m_g}} + h_{\mathrm{v}} \cdot j_{\mathrm{diff}}^{\mathrm{m_v}} + h_{\mathrm{voc,g}} \cdot j_{\mathrm{diff}}^{\mathrm{m_{voc,g}}} \right] + \sigma_{\mathrm{REV}}^{\mathrm{U}} \tag{6}$$

where $\rho_{\mathrm{REV}}^{\mathrm{U}}$ is the internal energy density in reference volume (J/m^3), $\sigma_{\mathrm{REV}}^{\mathrm{U}}$ is energy sources and sinks in reference volume (W/m^3), $j_{\mathrm{diff}}^{\mathrm{Q}}$ is heat conduction (W/m^2), j_{conv} is convective flux (kg/m^2·s), j_{diff} is diffusive flux (kg/m^2·s), m is mass, g is gas, v is vapour, l is liquid, u is specific internal energy (J/kg), h_{v} is the specific enthalpy of water vapour (J/kg), $h_{\mathrm{voc,g}}$ is the specific enthalpy of gaseous volatile organic compounds (J/kg).

3.5.2 Validation of the simulation model

The simulation model was calibrated on the basis of measurements in three stages. To determine the most important factors influencing the hygrothermal performance of the highly insulated timber frame wall, the initial simulation model was validated based on several laboratory tests of timber frame wall structures, performed at Tampere University of Technology (Kalamees and Vinha 2003). A section of timber frame wall structure used is shown in Figure 3.14 (left). Tests were made applying a shortened model for Nordic climate conditions from autumn to spring, see Figure 3.14 (right).

The hygrothermal performance of the PCLP wall without prefabricated timber frame insulation elements (i.e. before renovation) was analysed with a calibrated model, based on the field measurements records from a comparable project of a typical apartment building (series 1-464) where hygrothermal data of the PCLP wall in points 1 and 2 (see t1&RH1 and t2&RH2 in Figure 3.11, top) was collected for two years and then analysed (Ilomets and Kalamees 2013).

The agreement between model results and measurements was studied together with analysis of the hygrothermal performance of the PCLP wall with prefabricated timber frame insulation elements.

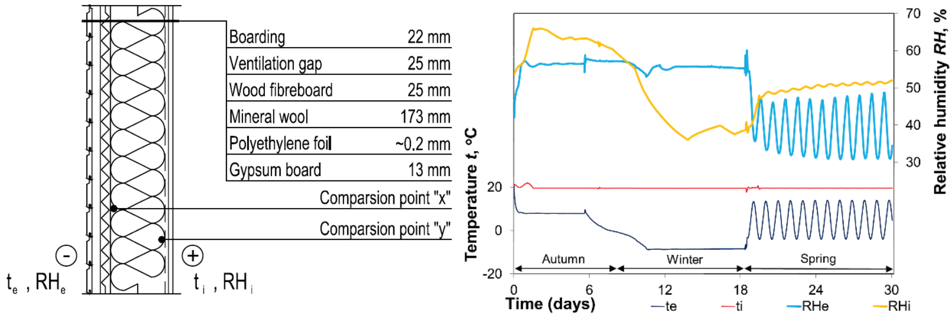


Figure 3.14 Vertical section of a structure used for the validation of the simulation model (left) and measured internal (i) and external (e) temperature (t) and relative humidity (RH) (right) (Kalamees and Vinha 2003). Reproduced from publication I.

3.5.3 Calculation models and conditions

As the hygrothermal performance of constructions is highly dependent on their moisture content (MC), the calculations with different initial *RH* or MC levels were performed to represent the critical conditions of various periods at the start of installation works at the building site:

- for timber frame wall: initial relative humidity *RH* = 80%; *RH* = 90%;
- for PCLP wall: initial moisture content (IMC) $w = 55$ kg/m^3; $w = 75$ kg/m^3; $w = 85$ kg/m^3; $w = 95$ kg/m^3; $w = 110$ kg/m^3.

The calculations of the IMC, dry-out capability and mould growth risk were performed for different periods:

- for highly insulated timber frame wall:
  - based on moisture reference year (MRY) (1989–1990);
- for PCLP wall before renovation:
  - based on MRY (1989–1990);
  - based on climate data from the weather station (1970–2015);
- for PCLP wall with prefabricated timber frame insulation elements:
  - based on MRY (1989–1990);
  - based on climate data from the weather station (1970–2017);
  - based on climate data measured on the building site (2017–2019).

To calculate the hygrothermal parameters in the critical points of the analysed structures, the detailed models of timber frame wall and PCLP wall with and without prefabricated insulation elements in the simulation software Delphin 5.8 were applied (see Figure 3.15).

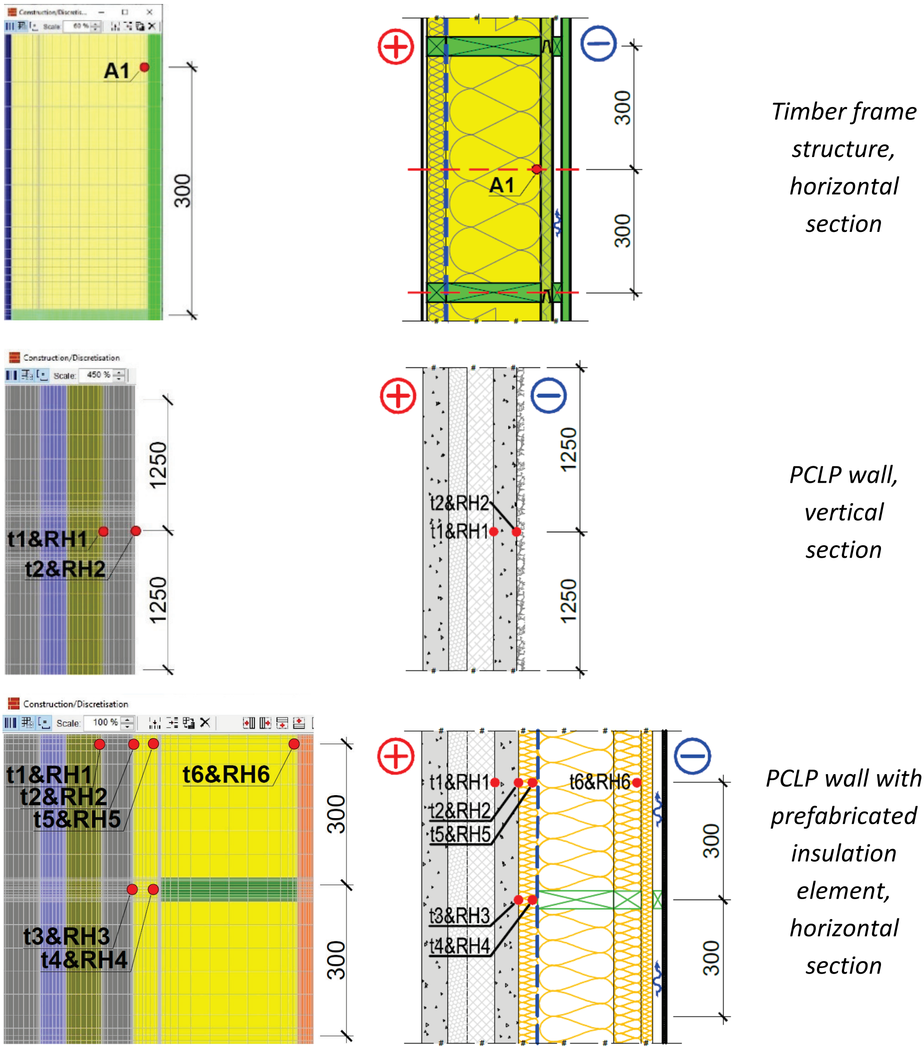


Figure 3.15 Overview of the calculation models in simulation software Delphin (left) and corresponding sections of the walls with analysed points (right). Based on figures from publications I (top), II (middle) and III (bottom).

3.5.4 Assessment of the risk of mould growth

The hygrothermal performance of the building envelope was evaluated based on the risk of mould growth. A mathematical model for the calculation of mould growth and decline as well as mould index in varying conditions (Hukka and Viitanen 1999, Ojanen et al. 2010) was used in this research.

According to this model, within fluctuating humidity conditions, the total exposure time for the response of the growth of mould fungi is affected by the time periods of high and low humidity conditions, as well as the humidity and temperature levels. In the simulation of mould growth, it is crucial to know the lowest (threshold) conditions where fungal growth is possible on different materials. The duration of these conditions is also significant. There are certain minimum and maximum levels for the moisture content of the material, water activity or temperature between which fungi can grow in wood.

Under these favourable conditions, mould growth may start and continue at different rates. The time period needed for the onset of mould growth and growth intensity are mainly dependent on water activity, temperature, exposure time and surface quality of the substrate. The boundary curve for the risk of mould growth in the temperature range between 5 and 40 °C on a wooden material can be described by a polynomial function:

$$RH_{\text{crit}} = \begin{cases} -0.00267 \cdot t^3 + 0.16 \cdot t^2 - 3.13 \cdot t + 100 & \text{when } t \le 20\ ^\circ\text{C} \\ RH_{\min} & \text{when } t > 20\ ^\circ\text{C} \end{cases} \tag{7}$$

where *t* is temperature (°C) on the surface of the investigated material and $RH_{\min}$ represents the minimum level of *RH* (%) where mould growth is possible (varies according to the sensitivity of the material, see Table 3.3). Determination of mould growth levels as indexes and corresponding descriptions are given in Table 3.4.

Table 3.3 Mould growth sensitivity classes, some corresponding materials and RH_{min} *values (Ojanen et al. 2010).*

Sensitivity class	Materials	$RH_{\min}$
Very sensitive	Untreated wood, sapwood	80%
Sensitive	Planed wood, paper-coated products, wood-based boards	80%
Medium resistant	Concrete, aerated and cellular concrete, mineral fibres, polyester wool	85%
Resistant	Glass and metal products, polyurethane polished surface	85%

Table 3.4 Description of mould indexes (Ojanen et al. 2010).

Mould index (*M*)	Description of mould growth
0	No growth
1	Small amounts of mould on surface (microscope), initial stage of local growth
2	Several local mould growth colonies on surface (microscope)
3	< 10% coverage, or < 50% coverage of mould (microscope)
4	10–50% coverage, or > 50% coverage of mould (microscope)
5	Plenty of growth on surface, > 50% coverage (visual)
6	Heavy and tight growth, coverage about 100%

For the analysis of the timber frame structure and PCLP wall of the pilot building, the mould index's critical level was set at $M = 1$ (see Table 3.4) and mould growth sensitivity class 'very sensitive' (i.e. untreated wood) or class 'sensitive' for treated timber, timber-based materials and gypsum board with paper in the installed on the pilot building prefabricated insulation elements and in the original envelope were assigned. For other materials used, class 'medium resistant' was set (see Table 3.3).

3.6 Commissioning of moisture safety

Applicable parts from existing quality assurance systems (SQUARE 2008, ByggaF 2013) and requirements from the local legislation and standards were implemented to describe the structure of commissioning and roles of participants to assess moisture safety. The Quality Assurance System SQUARE gives a good structural overview of the quality commissioning of the renovation process resulting in building management, maintenance and documentation procedures. The Industry Standard ByggaF is an applicable guide for moisture safety procedures and provides a well-structured overview of roles and responsibilities. Local regulation gives a quantitative input in the form of settled numerical limits and boundaries to be followed. For the design, production and construction processes of the pilot building, the framework of moisture safety was set up for:

- Moisture safety standard (i.e. what is the criterion or requirement to follow). The requirements are described at a general level in the Building Code (RT I, 21.12.2019), e.g. construction works must be designed, carried out and maintained according to good practice. Principles of safety, environmental soundness and professionalism must be followed;
- Metering standard (i.e. methods, tools and minimum input data for design and analysis). Standardised methodology must be implemented on measurements. Calibrated measuring equipment must be used. Dynamic simulation and calculation software with hourly stated climate data must be applied;
- Quality standard (i.e. requirement: moisture safety and metering standard is followed or not).

The moisture safety process of the current project involved the following roles and responsibilities:

- Planners and designers: a design company offering all design parts (chosen by the client from three candidates by using the best value method);
- Contractor: a prime contracting and project management company (chosen by the client from two candidates by using the best value method);
- Supplier: a producer of custom-made prefabricated timber frame houses and elements (chosen by the contractor);
- Moisture safety officer for planning: chief structural design engineer from the company that made the design of the renovation;
- Moisture safety officer for production: project manager of the contractor, owner's surveyor and the executive civil engineer from the supplier;
- Requirements for moisture safety for the design phase to be set in the design task and for construction in the design documentation;
- A moisture safety plan to be described in the design documentation;
- Moisture expertise to be conducted during the design phase;
- Moisture inspection to be conducted during the production and construction processes.

For contracting, quality assurance and production standards of sub-contractors (designer, supplier, contractor) were acceptable with the above listed requirements.

3.7 Material combinations and energy and cost calculations of prefabricated timber frame insulation elements for deep energy renovation

In this section, in total 1620 dimensional, conditional and material combinations of prefabricated timber frame insulation elements (see Figure 3.16) were analysed to find working sets for deep energy renovation of large concrete panel apartment buildings.

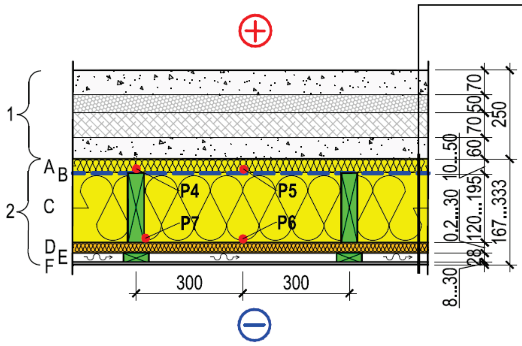
The cost (incl. production, installation and maintenance) and hygrothermal and energy performance were evaluated by means of quantitative analysis and handling in production and on installation by means of qualitative analysis (interviews and meetings at the factory and on the building site).

3.7.1 Analysed material combinations and building type

Materials for prefabricated timber frame insulation elements were combined considering the interaction of various parameters and conditions:

- Initial moisture content (IMC) of original concrete facade by volume: w = 85 kg/m^3, 95 kg/m^3, 110 kg/m^3 (i.e. IMC by mass (kg/kg): u = 3.7%, 4.1%, 4.7%);
- Air and vapour barriers (see Figure 3.16, layer B): vapour barrier with varying water vapour resistance, original wall without vapour barrier layer, PE-foil;
- Timber framing (see Figure 3.16, layer C): 45×120 mm, 45×145 mm, 45×195 mm;
- Types of insulation in prefabricated timber frame element (see Figure 3.16, layer C): mineral wool (MW), cellulose wool (CW); total thickness of insulation with 50 mm MW buffering layer (see Figure 3.16, layer A): 170 mm, 195 mm, 245 mm;
- Wind barriers (see Figure 3.16, layer D): sheathing membrane, gypsum board + sheathing membrane, fibre cement board, wood fibreboard, MW board with special wind barrier facing;
- Ventilated air gap with vertical timber battens (see Figure 3.16, layer E) 28×70 mm;
- Ventilated facade systems (see Figure 3.16, layer F): wooden boarding, plastic boarding/siding, metal profile sheets, cement fibreboards, facade stones cladding, plastered facade weatherboard.

The materials' properties of the studied structures are described in Table 3.2 and in publication VI, Table 1.



1. Original wall	
2. Prefabricated insulation element	
A. Buffering layer, MW, fixed with zigzag stripes (λ_U=0.037 W/(m·K))	10...50 mm
B. Air and vapour barrier (vapour resistance Z_p=1.6...27×10^9 (m^2·s·Pa)/kg)	~0.2 mm
C. Timber frame 45×120...195 mm,c/c 600 mm MW (λ_U=0.035 W/(m·K)) or CW (λ_U=0.045 W/(m·K))	120...195 mm
D. Wind barrier (vapour permeability δ_p≥11×10^{-12} kg/(m·s·Pa))	0.2...30 mm
E. Ventilated air gap, vertical timber battens 28×70 mm,c/c 600 mm	28 mm
F. Facade boarding (rainscreen)	8...30 mm

Figure 3.16 Horizontal cross-section of the original wall with installed prefabricated timber frame insulation element and analysed critical points. Scale 1 : 20. Reproduced from publication VI.

A typical five-story apartment building with total heated area of 2968 m^2, constructed of prefabricated concrete large panel elements in 1966 (serial project 1–464), was selected for the reference building (see Figure 2.1, left). This building type needs deep energy renovation because of serious thermal bridges (Ilomets, Kuusk, et al. 2017), high thermal transmittance of the external walls (U_{wall} = 0.8–1.5 W/(m^2·K)), insufficient performance of ventilation (Mikola et al. 2017), high indoor humidity loads (Ilomets, Kalamees, et al. 2017) and corrosion damages of concrete facades (Ilomets et al. 2016). Thermal transmittances of the studied structures are shown in Table 3.5.

*Table 3.5 Thermal transmittance U_c (W/(m^2·K)) * of analysed sets with different insulation materials (MW, CW) and wind barrier layers. See publication VI, Table 1 for description of layers D1…D5.*

Wind barrier layer	Thermal transmittance U_c, W/(m^2·K) * (frame thickness)					
	120 mm		145 mm		195 mm	
	MW	CW	MW	CW	MW	CW
D1	0.20	0.22	0.18	0.20	0.15	0.17
D2	0.20	0.22	0.18	0.20	0.15	0.17
D3	0.20	0.22	0.18	0.20	0.15	0.17
D4	0.18	0.20	0.17	0.18	0.14	0.16
D5	0.17	0.18	0.15	0.17	0.13	0.15

* Thermal transmittance is calculated with existing original wall construction ($R_{exist.wall}$ = 1 m^2·K/W).

3.7.2 Hygrothermal performance and simulations

Hygrothermal simulations with the software Delphin (see subsection 3.5.1) were conducted to analyse the performance of the external walls on the basis of values of temperature and relative humidity in critical points (see Figure 3.16, points P4, P5, P6 and P7).

To calibrate the calculation model in Delphin software program, field measurements were conducted in a pilot PCLP apartment building renovated in 2017 by using prefabricated timber frame insulation elements (see publication IV and publication V).

To assess the hygrothermal performance of the building envelope, the risk of mould growth was used as the criterion and mould growth model was implemented (see subsection 3.5.4). The safe value of the mould index (M) was set in the current stage of the study at $M < 1$ (no mould growth) and the critical value at $M = 2$ (several local mould growth colonies on surface). Therefore, the mould index $1 \leq M < 2$ is considered as a low risk of mould growth (small amounts of mould on surface, initial stage of growth) (Viitanen et al. 2015). Unprocessed (e.g. not planed) timber, belonging to the sensitivity class 'very sensitive', was not used in this phase of study.

As the hygrothermal performance of construction is highly dependent on moisture content, calculations of mould index with different initial moisture content levels of the original wall (w = 85 kg/m^3, w = 95 kg/m^3, w = 110 kg/m^3) were performed to represent the critical conditions of various periods of the start of installation works of the prefabricated timber frame insulation elements onto the existing envelope at the building site (see publication II).

3.7.3 Energy performance

In many countries, including Estonia, the energy performance of buildings is defined as an indicator, expressed as energy performance value (EPV) (kWh/(m^2·a)), of the total energy delivered into the building (i.e. heating, ventilation and air conditioning (HVAC) auxiliary, domestic hot water (DHW), lighting and appliances) multiplied with conversion factor (CF) taking into account the primary energy content and the environmental impact involved (e.g. $CF_{electricity} = 2.0$, $CF_{district\ heating} = 0.9$, $CF_{efficient\ district\ heating} = 0.65$). It is mandatory to fulfil the local decrees requirements of energy performance (RT I, 13.12.2018, RT I, 22.08.2019) for new and reconstructed by major renovation buildings. The energy performance criterion for a nZEB renovation (EPV ≤ 150 kWh/(m^2·a)) and for new buildings (EPV ≤ 125 kWh/(m^2·a) without local electricity production) was taken as the basis for evaluating energy efficiency of the studied solutions.

In addition to general energy performance of buildings, Estonian renovation grant scheme (RT I, 09.04.2019) sets the following criteria for renovation of apartment buildings:

- Thermal transmittance of building envelope:
  - $U_{external\ wall} \leq 0.20$ W/(m^2·K);
  - $U_{roof} \leq 0.12$ W/(m^2·K);
  - $U_{window} \leq 1.10$ W/(m^2·K);
- Installation of mechanical ventilation with heat recovery (MVHR). It means centralised plate heat exchanger or apartment based (plate or rotary thermal wheels heat exchanger) balanced ventilation (efficiency ≥ 80%) or exhaust ventilation with heat pump (efficiency ≥ 60%). In simulations MVHR with efficiency 75% was used;
- Full renovation of heating system. It means new insulated pipework and hydronic radiators with thermostats, DHW system and heating unit.

Energy performance of potential renovation solutions was modelled using the energy and indoor climate simulation program IDA Indoor Climate and Energy (IDA ICE 2018). This software allows the modelling of a multi-zone building, internal and solar loads, outdoor climate, heating and ventilation systems and dynamic simulation of heat transfer and airflows. It is validated and the building model is calibrated against field measurements (Kuusk, Kalamees, Link, et al. 2016). Input parameters to energy performance simulation were selected according to standard use condition from the Estonian regulations (RT I, 22.08.2019):

- Indoor temperature, heating set point 21 °C;
- Air flow rate for apartments with apartment-based air handling units (AHU) 0.42 l/(s·m^2) and apartments with central AHU 0.5 l/(s·m^2). Supply air temperature 18 °C;
- Standard use of DHW: 30 kWh/(m^2·a), i.e. 516 l/(m^2·a) at ΔT 50 K;
- Standard use of electricity: for appliances and lighting 29.5 kWh/(m^2·a); for circulation pumps 0.5 kWh/(m^2·a);
- Internal heat gains: occupants 15.8 kWh/(m^2·a) with usage rate 0.6 (representing average occupancy 28.3 m^2 per person); appliances and equipment: 15.8 kWh/(m^2·a) with usage rate 0.6; lighting 7.0 kWh/(m^2·a) with usage rate 0.1.

3.7.4 Cost efficiency

The global cost calculations were applied to assess the cost effectiveness of the renovation measures (EN 15459 2007). The renovation cost was calculated considering financing with loan in the amount of 85% and with self-financing of 15%, which is a common practice required by banks and the renovation grant organisation in Estonia for renovation projects of apartment buildings. The typical interest rate of 3% for apartment owners' associations was applied and the escalation of the delivered energy and maintenance prices was considered 1% in a year as an average (Statistics Estonia 2016). The energy prices used in calculations were 0.12 €/kWh for electricity and 0.06 €/kWh for district heating, as an average market level in 2019 in Estonia. The discount period 20 years as the longest loan period for apartment owners' associations in Estonia was applied. Global cost was calculated according to Equation (8):

$$C_{\mathrm{g}}(\tau) = \frac{C_{\mathrm{i}} + \sum_{\mathrm{i}=1}^{20} C_{\mathrm{a,i}}(\mathrm{j}) \cdot R_{\mathrm{d}}(\mathrm{i})}{A_{\mathrm{floor}}} - \frac{C_{\mathrm{g}}^{\mathrm{ref}}}{A_{\mathrm{floor}}} \quad \left(€/\mathrm{m}^2\right) \tag{8}$$

where $C_{\mathrm{g}}(\tau)$ is the global cost referred to the starting year (€/m²), C_{i} is the initial investment cost, self-financing of a renovation loan (€), $C_{\mathrm{a,i}}(\mathrm{j})$ is the annual cost of year i for the component j, energy and loan payback cost (€), $R_{\mathrm{d}}(\mathrm{i})$ is the discount rate for year i, $C_{\mathrm{g}}^{\mathrm{ref}}$ is the global cost of the reference building (€), A_{floor} is the net floor area (m²).

To obtain the realistic costs for construction, installation and maintenance, the comprehensive cost estimations were taken as basis from three companies producing and installing prefabricated timber frame elements. The average initial cost of their offers was used in cost efficiency calculations.

4 Results

The results of the research are divided into five main phases of hygrothermal analysis, measurements, calculations and development activities:

- Determination of hygrothermal parameters influencing highly insulated timber frame structures (calculations and simulations);
- Performance of the PCLP wall before renovation (measurements, calculations and simulations);
- Development of prefabricated timber frame insulation elements (prototyping, workshops, commissioning, calculations and simulations);
- Performance of the PCLP wall after the renovation with prefabricated timber frame insulation elements (measurements, calculations and simulations);
- Material combinations, energy and cost calculations of prefabricated timber frame insulation elements for deep energy renovation (workshops, interviews, calculations and simulations).

4.1 Calibration of simulation models in different phases of the study

4.1.1 Model for the highly insulated timber frame structure

Comparison of accurate laboratory measurements (see Figure 3.14) and simulations (see Figure 4.1) showed good agreement. It confirms the matching of the calculation results for the simultaneous spread of unsteady heat and moisture obtained with the help of calculation software with the results of laboratory tests. In the light of the above, the use of such software for the analysis of timber frame insulation elements as well as for the assessment is considered eligible in the course of the current research work.

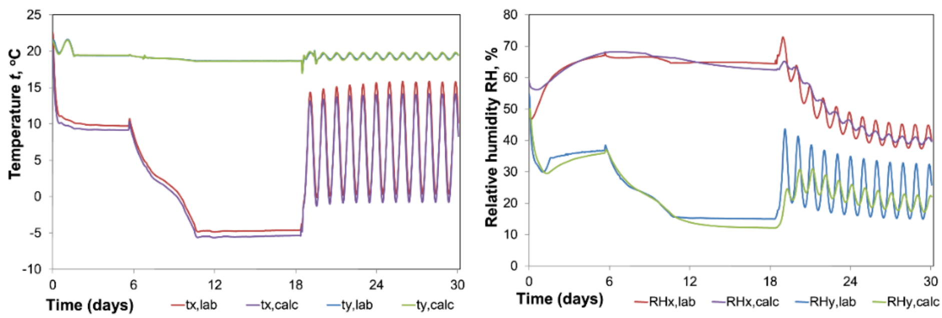


Figure 4.1 Temperature t (left) and RH (right) laboratory measurements (lab) and simulations (calc) of two comparison points, shown in Figure 3.14 (left). Reproduced from publication I.

4.1.2 Model for the PCLP wall

The influence of moisture dry-out from the prefabricated concrete large panel (PCLP) wall on the hygrothermal performance of prefabricated insulation elements was simulated during the design phase, and good agreement of measurements and simulation results was achieved, see Figure 4.2.

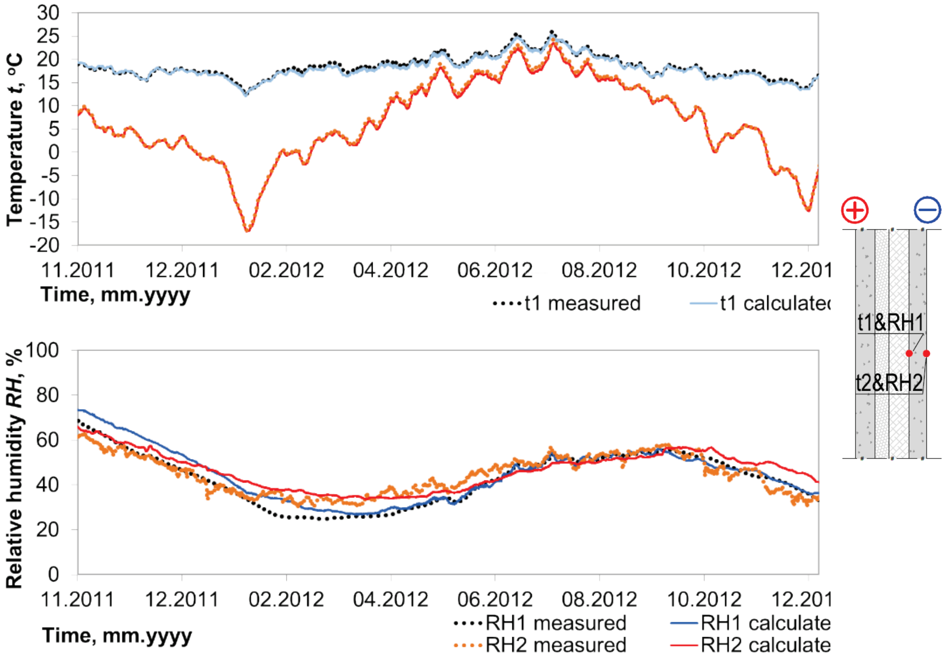


Figure 4.2 Measured and calculated temperature (top) and RH in the PCLP wall. See points 1 and 2 in Figure 3.11 (top). Reproduced from publication II.

After the construction works on a pilot building, the simulation was compared with the measurements in critical points (see Figure 3.11, bottom) to see whether the initial expectations and the results were in good agreement. Results of the measurements and simulation of the post-renovation phase are described and discussed in the subsequent chapters (see Figure 4.31 and Figure 4.32).

4.2 Parameters influencing the hygrothermal performance of the highly insulated timber frame structure

Analysis revealed differences between mineral wool (MW) and cellulose wool (CW) in the dry-out capability and in moisture formation risks, together with a change of the thermal transmittance and initial relative humidity (*RH*) level. Even though the wall with thermal transmittance $U = 0.17$ W/(m^2·K) was designed to meet the determined mould index criterion $M < 1$, in case the thermal resistance was increased (i.e. by an increase of the insulation thickness) without changing other material layers in the structure, the mould growth risk increased and mould index $M > 1$. See results of the analysis in Figure 4.3 and Figure 4.4.

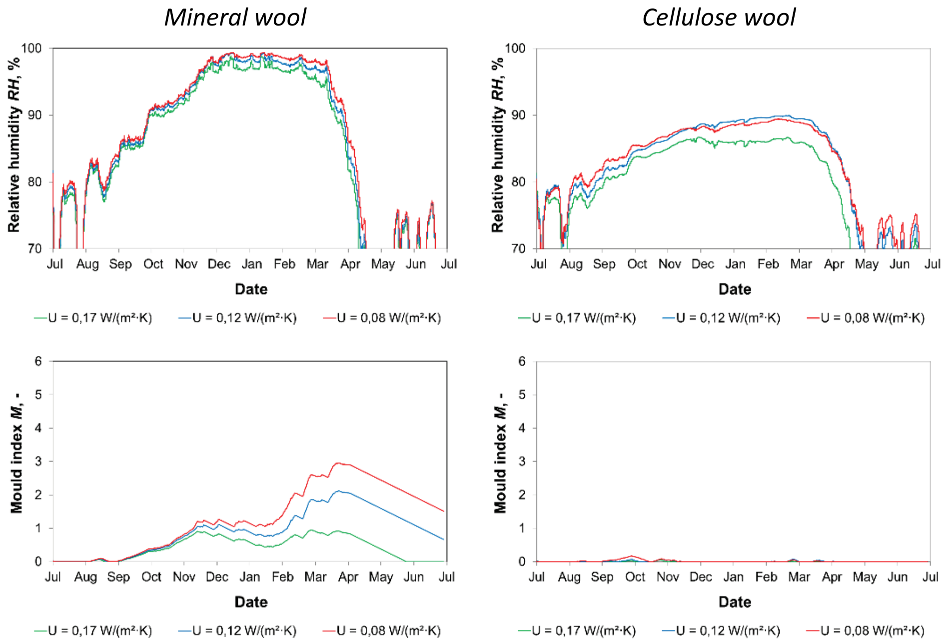


Figure 4.3 *Dependence of RH (above) and mould index (below) on thermal transmittance. Initial RH = 80%. See the analysed critical point between the wind barrier and insulation layer (A1) in Figure 3.1. Reproduced from publication I.*

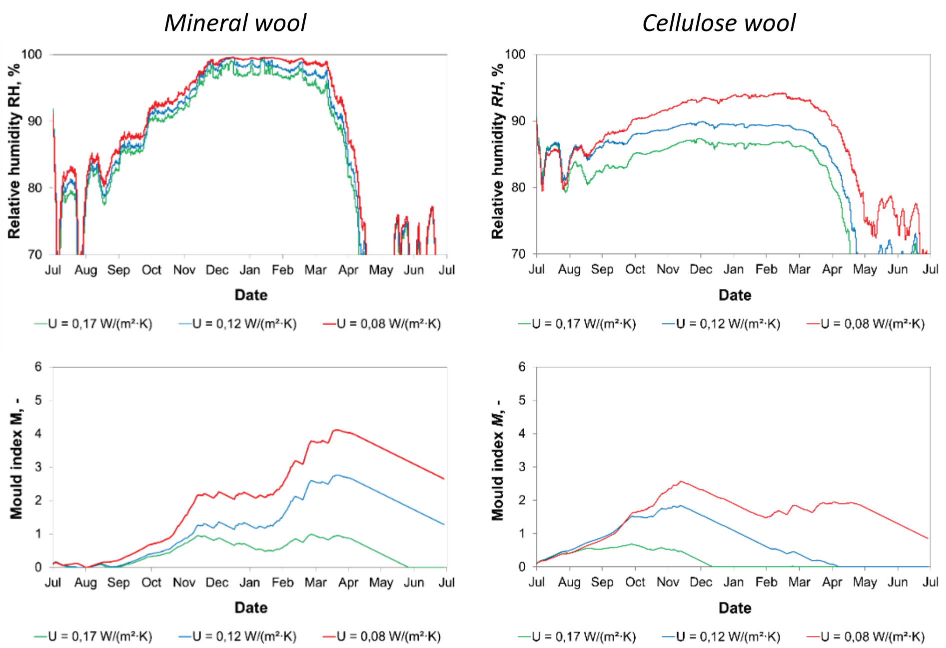


Figure 4.4 *Dependence of RH (above) and mould index (below) on thermal transmittance. Initial RH = 90%. See the analysed critical point between the wind barrier and insulation layer (A1) in Figure 3.1. Reproduced from publication I.*

Figure 4.5 (top) shows how the exterior wall with no mould growth risk ($M < 1$) and with thermal transmittance $U = 0.17$ W/(m^2·K) may become ineligible in terms of moisture safety because of the changed wind barrier but unchanged, i.e. non-effectual air and vapour barrier, if $U < 0.17$ W/(m^2·K). The air and vapour barrier (kraft paper A) remained the same in all analysed cases in Figure 4.5 (top). The mould index of the wall with oriented strand board (OSB) or with gypsum board wind barrier is above the critical value ($M > 1$). The reason is the higher *RH* behind these boards because of their lower water vapour permeability and lower thermal resistance. At the same time, the structure with 25 mm MW wind barrier board stays below the critical mould growth level ($M < 1$) due to its high water vapour permeability and thermal resistance.

Figure 4.5 (bottom) demonstrates the required minimum thermal resistance (R, m^2·K/W) of the wind barrier layer and concurrent water vapour permeability of the air and vapour barrier layer for walls with different thermal transmittances to stay below the mould growth risk ($M < 1$). As wind barriers, 22 mm wood fibreboard, 12 mm OSB and 9 mm gypsum board with an additional insulation layer on the external side were compared. To achieve the required thermal resistance of the wind barrier layer, MW of different thickness was added. To stay below the limit of mould growth (i.e. $M < 1$), the additional MW layer needed on top of the wind barrier may reach even 100 mm, which is probably not cost-efficient and is technologically difficult to realise.

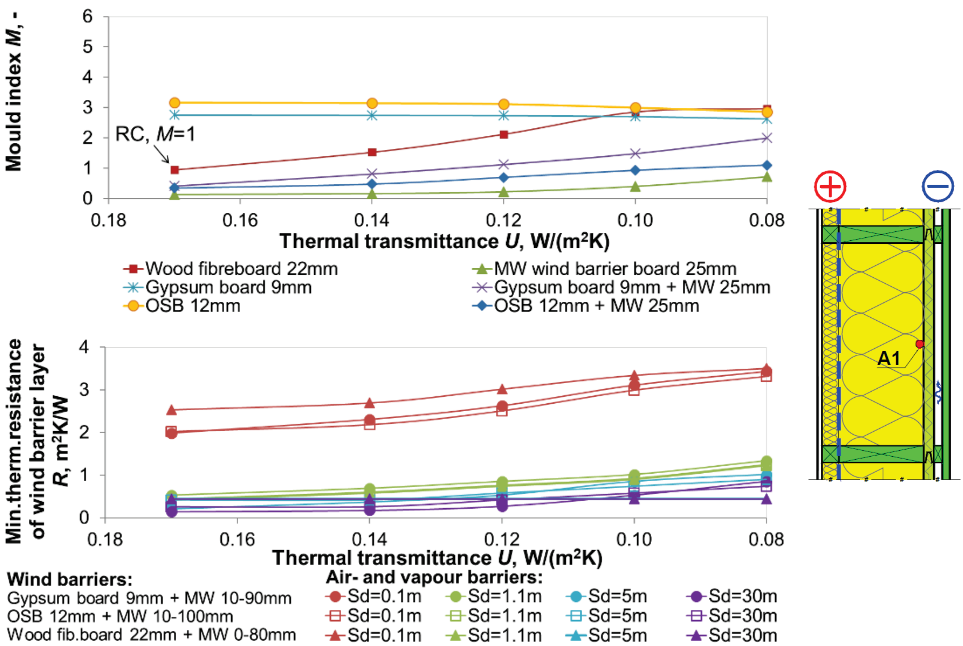


Figure 4.5 *Dependence of mould growth risk between the wind barrier and MW insulation layer (top). The required minimum thermal resistance (R) of a wind barrier layer of walls with common air and vapour barrier materials, shown by their S_d values (0.1 m ≤ S_d ≤ 30 m) if mould index M < 1 (bottom). See analysed point A1 in Figure 3.1. Reproduced from publication I.*

Common air and vapour barrier materials were used, described via their water vapour diffusion resistance (0.1 m ≤ S_d ≤ 30 m). Vapour barriers with relatively high water vapour permeability are not always acceptable in case of lower thermal transmittances of a building envelope without additional insulation on the wind barrier's external side (to keep the *RH* low).

The required minimum thermal resistance of the wind barrier layer of walls with thermal transmittances 0.08 ≤ U ≤ 0.17 W/(m²·K), insulated with MW or CW and with common air and vapour barrier materials, if mould index M < 1, is shown in detail in publication I, Table 3.

4.3 Moisture content and dry-out capability analysis of the PCLP wall

4.3.1 Measurements of the moisture content of the PCLP wall

During the construction works, before the installation of prefabricated timber frame insulation elements, samples from PCLP walls of the pilot building were drilled out (see Figure 4.6) and lab measurements of moisture content (MC) were performed.

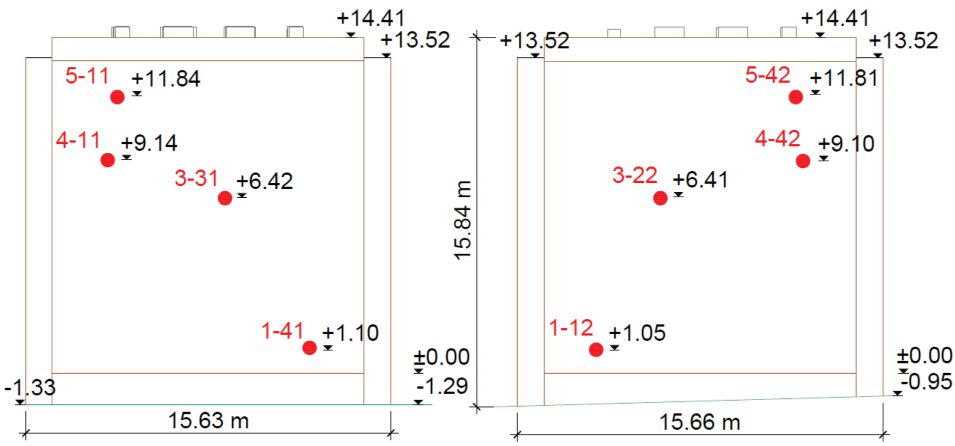


Figure 4.6 *Locations of drilled-out samples on the PCLP facade to measure moisture content during the construction works. View of west facade (left) and east facade (right).*

The results of the measurements of MC of drilled-out samples of the PCLP wall are below the critical limit (w = 110 kg/m³) and in agreement with corresponding simulations of average MC loads in spring and summer seasons (see Figure 4.7).

Table 4.1 *Measurements of moisture content of samples of PCLP during the construction works in 2017, before the installation of prefabricated timber frame elements. See Figure 4.6 for measurement points.*

Sample No.	1-41	3-31	4-11	5-11	1-12	3-22	4-42	5-42
Diameter d, mm	94.2	94.5	93.9	94.1	43.5	43.3	43.4	43.3
Dry density ρ, kg/m³	2313	2160	2185	2036	2045	2124	2155	2094
Moisture content w, kg/m³	53.9	76.7	53.6	60.7	43.3	62.7	63.1	54.9
Moisture content u, %	2.33	3.55	2.45	2.98	2.12	2.95	2.93	2.63

4.3.2 Analysis of the PCLP wall – pre-renovation phase

The initial examination of the MC of PCLP with the impact of wind-driven rain (WDR) was done in four main orientations: north, east, south and west. The MC (*w*, kg/m^3) was calculated for the whole studied period of 43 years (1970–2012) for different orientations of walls and results were analysed on a monthly basis. The results (see Figure 4.7) showed a higher impact of WDR on MC on the top corners of walls on the western and southern sides of the building: the maximum MC there was about 15–20% higher than on the northern and eastern sides.

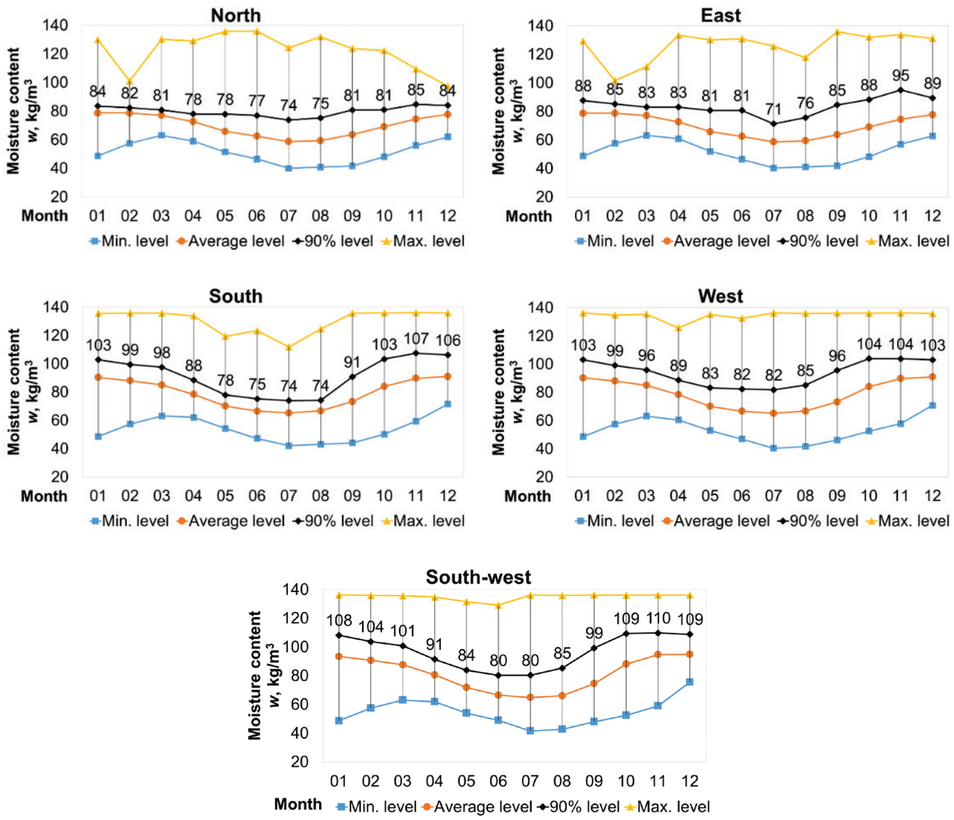
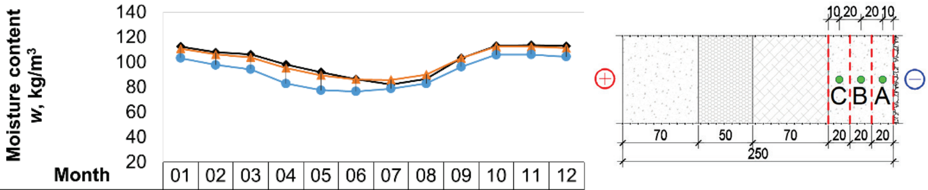


Figure 4.7 Monthly distribution of MC in the top corners of the exterior 60 mm concrete slab of PCLP wall in N, E, S, W and SW orientations with WDR during the studied period (1970–2012). Reproduced from publication II.

The results showed the highest MC to occur in the last quarter and the first months of the year in the south-west (SW) orientation. The initial moisture content (IMC) in the exterior 60 mm concrete slab of the PCLP wall (see Figure 3.11 top, pos. 5) of that period with the impact of wind-driven rain (WDR) was 137 kg/m^3 as maximum, 110 kg/m^3 as 90% level and 90 kg/m^3 as an average. The minimum, average, maximum and 90% levels are the results from the ranking of months from all years of the studied 43-year period (1970–2012).

Subsequently, analysis of the moisture load was continued with the SW wall as the most critical by considering the WDR load, and the MC in different zones of the PCLP was analysed (see Figure 4.8, right). Figure 4.8 (left) illustrates the MC redistribution and results of the 90% level of each calculated point (A, B and C) and the 90% level of moisture distribution in the entire exterior slab of the PCLP wall in the SW orientation. The highest MC in the whole 60 mm exterior slab of the PCLP wall was determined in November (w = 110 kg/m^3).



Month	01	02	03	04	05	06	07	08	09	10	11	12
90% level pt. C	113	108	106	98	92	86	82	87	103	113	114	113
90% level pt. B	111	106	104	95	90	86	86	90	103	112	112	111
90% level pt. A	103	98	94	83	77	77	79	83	96	106	106	104
90% level {A-B-C}	108	104	101	91	84	80	80	85	99	109	110	109

Figure 4.8 *Monthly distribution of MC in the exterior slab of the PCLP wall in the SW orientation with WDR in points A, B, C (left) of the studied period (1970–2012). Schematic layout of the analysed zones and points A, B, C (right) in the exterior concrete slab of the PCLP wall (see detail 1.1 in Figure 3.11, top). Reproduced from publication II.*

The MC of the exterior slab of the PCLP wall showed correlated dynamics with rainfall, see randomly chosen period in Figure 4.9. The potential of moisture dry-out from the exterior slab of PCLP was analysed in connection with dependence on WDR and the consecutive dry (without rain) days after rainfall (see Figure 4.10).

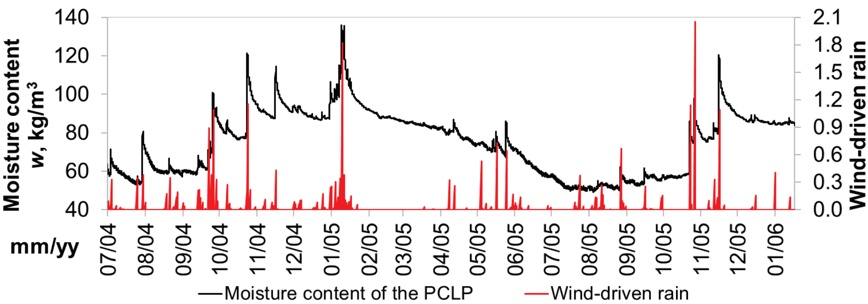


Figure 4.9 *Correlative change of MC in the exterior slab of the PCLP wall in the SW orientation with WDR during the randomly chosen period. Reproduced from publication II.*

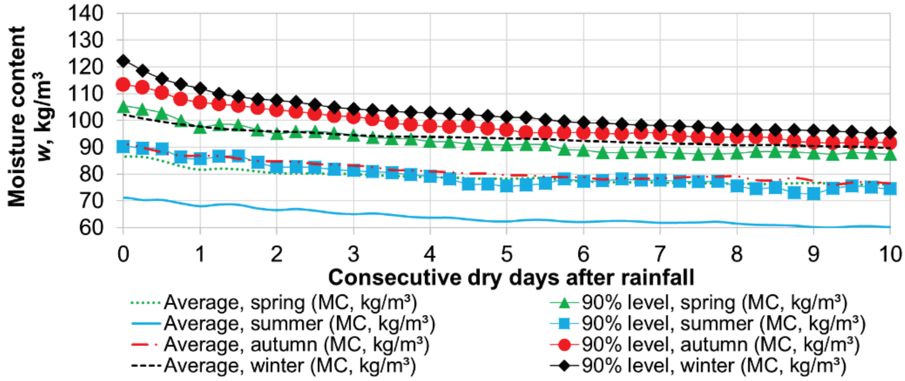


Figure 4.10 Moisture dry-out in the exterior slab of the PCLP wall in the SW orientation during the studied period (1970–2012) in consecutive 10 dry days after rainfall in different seasons of the year. Reproduced from publication II.

Results show variance of the speed of moisture dry-out and MC levels in different seasons of the year. The dry-out is relatively fast within the first 1–2 days after rain and practically stops after 7–9 days. A quicker drop of the MC can be observed in case of higher starting levels ($w \geq 100$ kg/m^3). From the level $w = 120$ kg/m^3 the MC drops in 2 days after rainfall to the level 107 kg/m^3 while from the starting level of 90 kg/m^3 it drops in 2 days down to 82 kg/m^3. The concrete slab dry-out after rainfall is in the range 5–20 kg/m^3 in 10 days, depending on the seasonal conditions and respective initial moisture content.

4.4 Development of prefabricated timber frame insulation elements for deep energy renovation of the PCLP wall

4.4.1 Design analysis of the PCLP wall insulated with prefabricated elements

The analysis of the influence of moisture dry-out from the PCLP wall insulated with prefabricated timber frame elements was started with simulations in points 3, 4, 5 and 6 (see t3&RH3, t4&RH4, t5&RH5 and t6&RH6 in Figure 3.11, bottom). The IMC of the exterior slab of the PCLP wall was set at $w = 110$ kg/m^3 as the starting state, representing the most critical season of the year and wall orientation to SW as the most critical to WDR. After that, *RH* was followed in points 3, 4, 5 and 6 throughout a 5-year period. Polyethylene (PE) foil as a first choice of the air and vapour barrier for timber frame structures in cold climate conditions was proposed by the pilot project designer.

The highest RH was observed on the inner surface of the PE-foil in point 4 (see t4&RH4 in Figure 3.11, bottom). At this location, the insulation was in saturation state (*RH* close to 100%) for more than 3½ years. For more than a year, *RH* of 100% was detected on the inner surface of the PE-foil in point 5 (see t5&RH5 in Figure 3.11 (bottom) and P5 in Figure 4.11). In point 3 and point 6, the RH dropped in the course of 3–4 months to the level of equilibrium state and thereupon followed normal weather dynamics (see t3&RH3 and t6&RH6 in Figure 3.11 (bottom) and P3 and P6 in Figure 4.11).

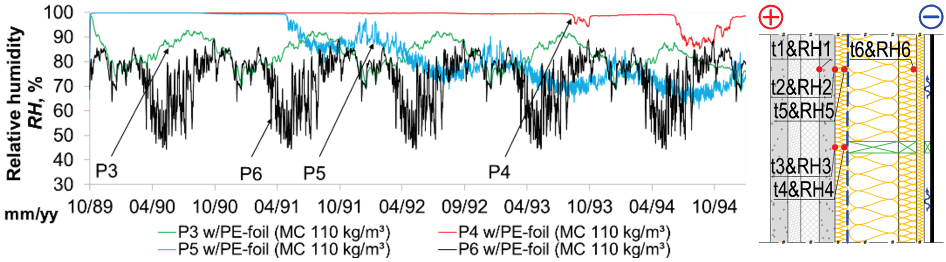


Figure 4.11 RH in the analysed points 3, 4, 5 and 6 with PE-foil as the air and vapour barrier layer in a 5-year period when the IMC of the PCLP wall w = 110 kg/m³. See Figure 3.11 (bottom) for points t3&RH3, t4&RH4, t5&RH5 and t6&RH6. Reproduced from publication III.

Analysis was continued in the most critical with regard to hygrothermal performance point 4 (see t4&RH4 in Figure 3.11 (bottom) and P4 in Figure 4.11), i.e. on the inner surface of the PE-foil air and vapour barrier, where the highest *RH* level in the analysed period was observed. In this location, the *RH* was calculated with different air and vapour barriers and control layers and with a number of IMC levels of the 60 mm exterior slab of the original PCLP wall (75 kg/m^3, 90 kg/m^3 and 110 kg/m^3) in order to replicate the 90% level moisture loads in different seasons and at the same time, compare the impact of moisture load with different air and vapour control layers.

The lowest moisture load at the monitored point 4 (see t4&RH4 in Figure 3.11, bottom) within a 5-year period was detected in the analysed structure without an air and vapour barrier layer and the highest level was reached with the solution where PE-foil was used as the air and vapour barrier layer if the IMC of the PCLP wall was set at w = 110 kg/m^3 (see Figure 4.12).

Since the absence of a vapour barrier poses a high risk in case of sudden leakages or cracks in the original wall and PE-foil will cause a consistent condensation state between the original wall and the prefabricated timber frame element, these choices were discarded. As a result, it was decided to continue with vapour barrier with varying vapour resistance (0.2 m ≤ S_d ≤ 5 m) as the vapour control layer (see VVR in Figure 4.12), allowing a controlled water vapour flow through the structure.

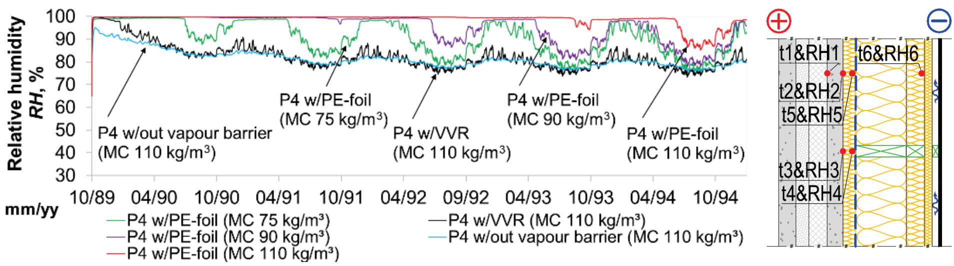


Figure 4.12 RH on the inner surface of the air and vapour barrier in point 4 (see point t4&RH4 in Figure 3.11, bottom) with different vapour control layers and different IMC of the PCLP wall in a 5-year period. Reproduced from publication III.

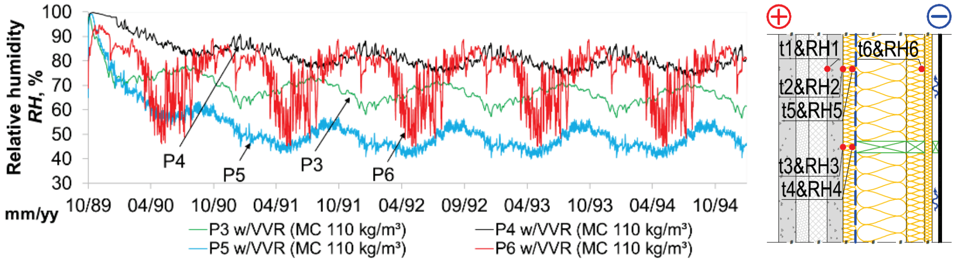


Figure 4.13 RH in points 3, 4, 5 and 6 with a vapour barrier with varying vapour resistance (0.2 m ≤ S_d ≤ 5 m) in a 5-year period when the IMC of the PCLP wall w = 110 kg/m³. See Figure 3.11 (bottom) for analysed points. Reproduced from publication III.

The analysis was continued with monitoring the *RH* in points 3, 4, 5 and 6 (see points t3&RH3, t4&RH4, t5&RH5 and t6&RH6 in Figure 3.11, bottom) throughout a 5-year period when a vapour barrier with varying vapour resistance (0.2 m ≤ S_d ≤ 5 m) as the air and vapour control layer (see VVR in figures) was used and the IMC of the exterior slab of the PCLP wall was set at *w* = 110 kg/m³. The *RH* in the monitored points dropped after initiation relatively quickly and reached an equilibrium state in the course of 4–6 months (see Figure 4.13), which is longer than it was with PE-foil. The highest level of *RH* throughout the calculated period was observed in point 4, between the original PCLP wall and the air and vapour barrier. The overall trend of *RH* in point 6 (behind the wind barrier) was slightly higher than in the first stage of simulations with PE-foil (see Figure 4.11).

The next phase of the assessment of moisture dry-out capability and hygrothermal performance was conducted with the calculation of mould indexes (M) in monitored points 3, 4, 5 and 6 (see points t3&RH3, t4&RH4, t5&RH5 and t6&RH6 in Figure 3.11, bottom). The rating 'very sensitive' in the sensitivity classification was initially given to the materials in the structure described in the mould growth model as a class of untreated wood with lots of nutrients for biological growth. These calculations gave unsatisfactory results (i.e. M > 1) in points 3, 4 and 5 (see Figure 4.14).

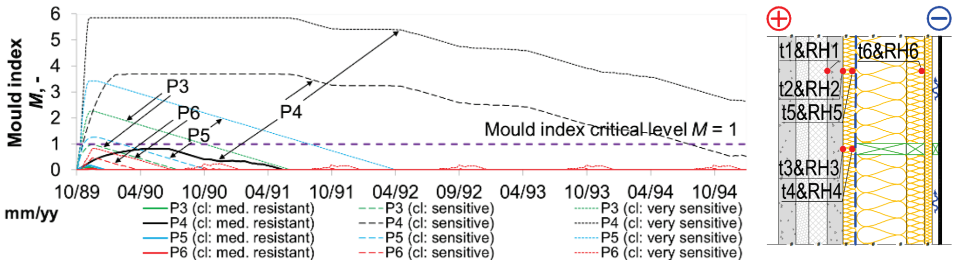


Figure 4.14 Mould index (M) with different sensitivity classes in points 3, 4, 5 and 6 in a 5-year period with a vapour barrier with varying vapour resistance (0.2 m ≤ S_d ≤ 5 m) when the IMC of the PCLP wall w = 110 kg/m³. See Figure 3.11 (bottom) for analysed points. Reproduced from publication III.

At the next step, the sensitivity class 'sensitive' was applied, which is described as a class for planed wood, paper-coated and wood-based products. In the most critical point 4 (t4&RH4) and in point 5 (t5&RH5) the mould index exceeded the critical level (*M* > 1). Considering the properties of construction and materials in the analysed structure points, the sensitivity class was switched to 'medium resistant', which is the class for cement or plastic-based materials and mineral fibres and describes the situation in monitored hereby points most accurately. The mould index was recalculated and in the most critical point 4 (t4&RH4) the result obtained was under the critical level ($M < 1$). Moreover, no noteworthy mould formation was detected in other analysed points (3, 5 and 6) in this calculation stage.

As an alternative, the solution with OSB instead of a thin rolled vapour retarder as the vapour control layer was examined. To evaluate this solution the *RH* in point 4 (t4&RH4) was observed throughout a 2½ year period and mould index was calculated with 22 mm OSB and the IMC of the original PCLP exterior slab $w = 75$ kg/m^3 or 110 kg/m^3. The calculation results indicated a gradual drop of the *RH* level in monitored point 4 to its equilibrium state in the course of 8–10 months, followed by a period of normal weather dynamics.

Subsequently, the mould index *M* was calculated with the same conditions with mould growth sensitivity class 'sensitive', following the properties of the wood-based OSB. The results indicated that the mould index remained under the critical level ($M < 1$) when the IMC of the original PCLP exterior slab $w \leq 75$ kg/m^3, meaning basically a situation without a WDR load. When the IMC of the original PCLP exterior slab $w > 75$ kg/m^3, the mould index calculations gave unsatisfactory results (i.e. $M > 1$) in point 4 (t4&RH4).

The mould index was calculated also in point 4 (t4&RH4) with the originally designed solution, where PE-foil was to be used as the air and vapour barrier layer and the IMC of the original PCLP exterior slab $w = 75$ kg/m^3, 90 kg/m^3 or 110 kg/m^3. With the stated IMC levels and with all mould growth model sensitivity classes, the calculated mould index exceeded the critical level to a large extent ($M > 3$). Calculations of the mould index in point 4 (t4&RH4) with PE-foil used as the air and vapour barrier layer gave satisfactory results (i.e. $M < 1$) in sensitivity class 'medium resistant' only in cases where the IMC of the original PCLP exterior slab $w \leq 55$ kg/m^3. Calculations with higher sensitivity classes ('sensitive' and 'very sensitive') gave unsatisfactory results (i.e. $M > 1$) in point 4 (t4&RH4), which indicates that in this type of structure the use of untreated wood and wood- or paper-based materials with PE-foil (or materials with similar vapour resistance) is not allowed.

Thus, meeting the requirements of the hygrothermal performance was ascertained in point 4 (t4&RH4) with vapour barrier with varying vapour resistance (0.2 m $\leq S_d \leq$ 5 m) when the IMC of the exterior slab of the original PCLP wall $w \leq 110$ kg/m^3 or with 22 mm OSB when the IMC of the exterior slab of the original PCLP wall $w \leq 75$ kg/m^3 or with PE-foil when the IMC of the exterior slab of the original PCLP wall $w \leq 55$ kg/m^3. In all these solutions the insulation layer of the prefabricated elements ($R \geq 7.5$ m^2·K/W; $S_d \leq 0.5$ m) was covered with a 30 mm MW wind barrier board with special facing ($R \geq 0.8$ m^2·K/W; $S_d \leq 0.05$ m) and with firm weatherproof facade boarding.

4.4.2 Concept of the deep energy renovation of the apartment building

The concept of the deep energy renovation of the pilot PCLP apartment building included a complex of various measures with an expectation of about 60–70% of energy savings compared to the pre-renovation state. Several measures improving the energy efficiency and technical appliances were planned to be installed, which all together would classify this building after its deep energy renovation as nZEB (Kuusk and Kalamees 2015, Kalamees et al. 2016).

The building envelope above ground (walls and roof) was planned to be insulated with prefabricated timber frame insulation elements. Basement walls were planned to be insulated in situ with an ETICS. Prefabricated roof insulation elements were designed to be installed on the specially built timber framework because the original roof had an inward slope and a parapet. Under the formed new slope roof with eaves stepping out from the perimeter, in the 0.6–1.2 m high attic between the old and the new roof, technical appliances (e.g. heat exchangers, duct dispensers, automatics etc.) were planned to be placed. Preheated air supply ducts embedded into the prefabricated wall insulation elements would spare space in the apartments. In addition to the use of prefabricated insulation elements, the design solution included many other tasks such as parallel comparison of two different ventilation solutions: apartment-based balanced ventilation with heat recovery (VHR) in half of the building and centralised balanced VHR (‘engine’ is placed into the ventilation chamber built onto the roof) for the other half of the building; parallel comparison of providing DHW by solar collectors and greywater heat recovery. Solar collectors and photovoltaic panels were designed onto the roof for efficient energy production together with a fully renovated 2-pipe district heating system with radiators and thermostats. The ventilation airflow after renovation should represent a normal level of expectation for indoor climate class II (ICC II) (RT I, 09.04.2019).

The full renovation of the pilot PCLP apartment building was completed in 2017 as an Estonian pilot in the EU Horizon2020 funded project of developed and advanced prefabrication of innovative, multifunctional building envelope elements for modular retrofitting and connections (MORE-CONNECT) (Veld 2015, Rovers et al. 2018). The prefabricated timber frame insulation elements were produced, delivered and installed on the pilot building by AS Matek, the producer of timber-based elements and modules.

Figure 4.15 Overview of the pilot PCLP apartment building in 2015 before (left), in summer 2017 during (middle) and in autumn 2017 after (right) its deep energy renovation with prefabricated timber frame insulation elements. Photos from publication V.

4.4.3 Design of prefabricated timber frame insulation elements

The thickness of the prefabricated timber frame wall elements is 340–380 mm, depending on the surface flatness of the original PCLP wall. The timber frame structure (see Figure 4.17 top, pos. 4 and pos. 5) is filled with 265 mm MW in two layers, 195 mm + 70 mm (ρ = 22 kg/m^3; $R \geq 7.5$ m^2·K/W; $S_d \leq 0.5$ m), and covered with 30 mm MW wind barrier board (ρ = 104 kg/m^3; $R \geq 0.8$ m^2·K/W; $S_d \leq 0.05$ m) from the exterior side (see Figure 4.17 top, pos. 6). The inner side of the element is covered with an air and vapour barrier with varying vapour resistance (0.2 m $\leq S_d \leq$ 5 m) (see Figure 4.17 top, pos. 3). The 25 mm ventilated air gap (see Figure 4.17 top, pos. 7) with vertical timber battens (c/c 600 mm) is covered with 8 mm facade hardboard, which provides a firm rainscreen to the structure beneath (see Figure 4.17 top, pos. 8). The thermal transmittance of wall type 1 (i.e. PCLP wall + prefabricated timber frame insulation element) after the renovation $U_{wall1} \leq 0.11$ W/(m^2·K). The basement on-ground and underground walls of the PCLP pilot building were designed to be insulated in situ with an ETICS where 320 mm thick expanded polystyrene (EPS) is used and $U_{b.wall} \leq 0.10$ W/(m^2·K). The thickness of the thermal insulation in the roof insulation elements (see Figure 4.18) is 340 mm and $U_{roof} \leq 0.10$ W/(m^2·K).

To get information about the unevenness and roughness of the original PCLP surface (Figure 4.16, left) and inhomogeneity of the location of windows, 3D laser scanning of the whole envelope was conducted before the design. To smooth the roughness of the original wall, 50 mm MW (ρ = 20 kg/m^3) as the buffer layer was added onto the back side of the prefabricated element (see Figure 4.17 top, pos. 2). This < 50 mm light buffering layer was fixed in a zigzag pattern with strings (see Figure 4.16, right), which were released after the element was installed.

The exterior slabs of the PCLP (see Figure 3.11 top, pos. 5) were strengthened with anchors (see Figure 4.17) to transmit the load of added elements. Therefore, there was no need for a foundation for the installed wall elements. Self-supporting timber frame elements were hung onto the original PCLP wall surface with specially designed steel brackets, allowing adjustment of elements in all three directions up to ±25 mm on installation (see Figure 4.19, left).

Figure 4.16 The original PCLP wall surface was rough and uneven (left). To smooth the surface, a buffering layer was attached on the back side of the prefabricated insulation elements (right) (2017).

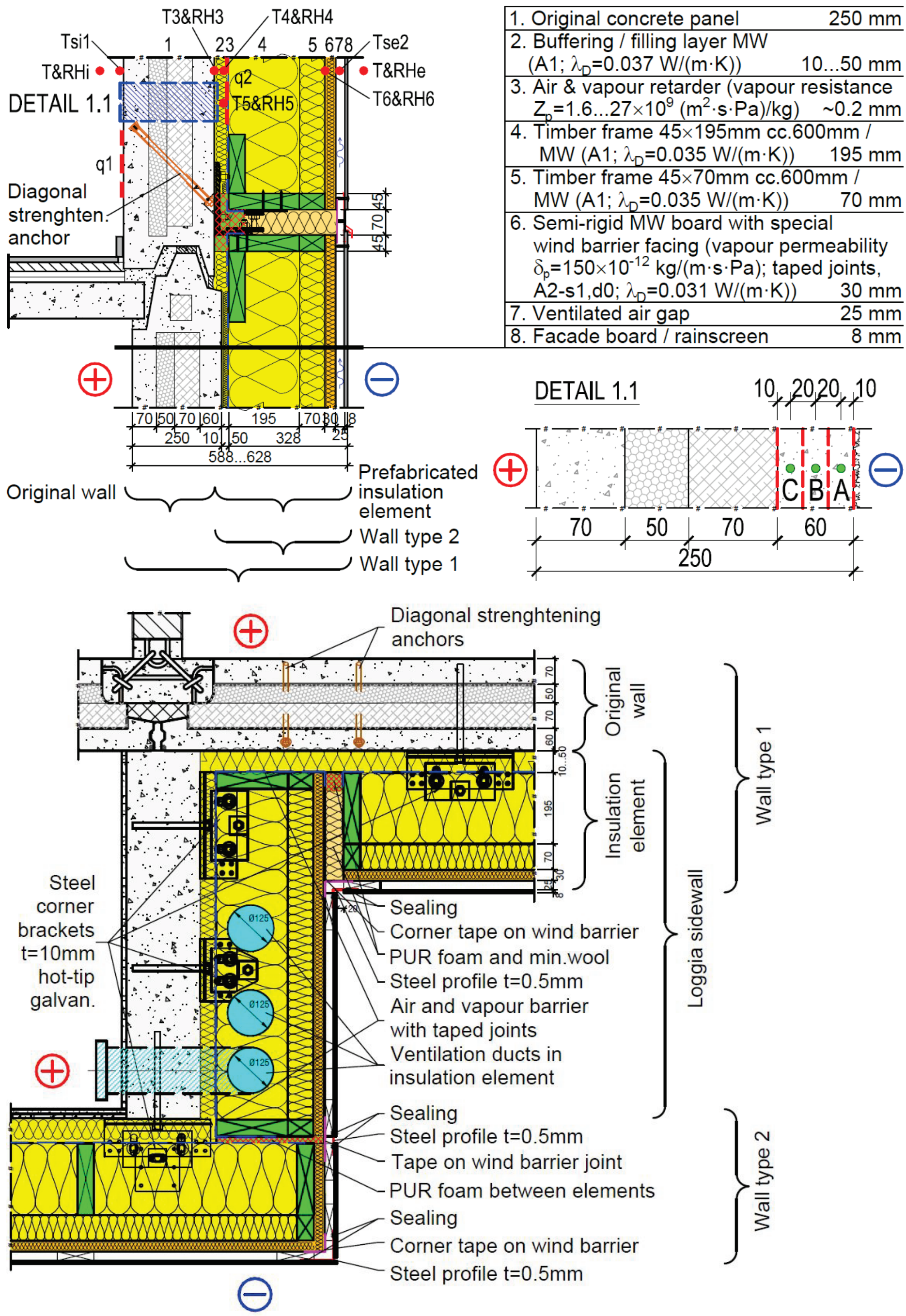


Figure 4.17 Final design solution of the PCLP wall with prefabricated timber frame insulation elements, vertical section (top). Loggia sidewall with embedded into the prefabricated element ventilation ducts, horizontal section (bottom). Greyscale – original PCLP; coloured – prefabricated timber frame insulation elements. Scale 1 : 20. Adapted from publication IV.

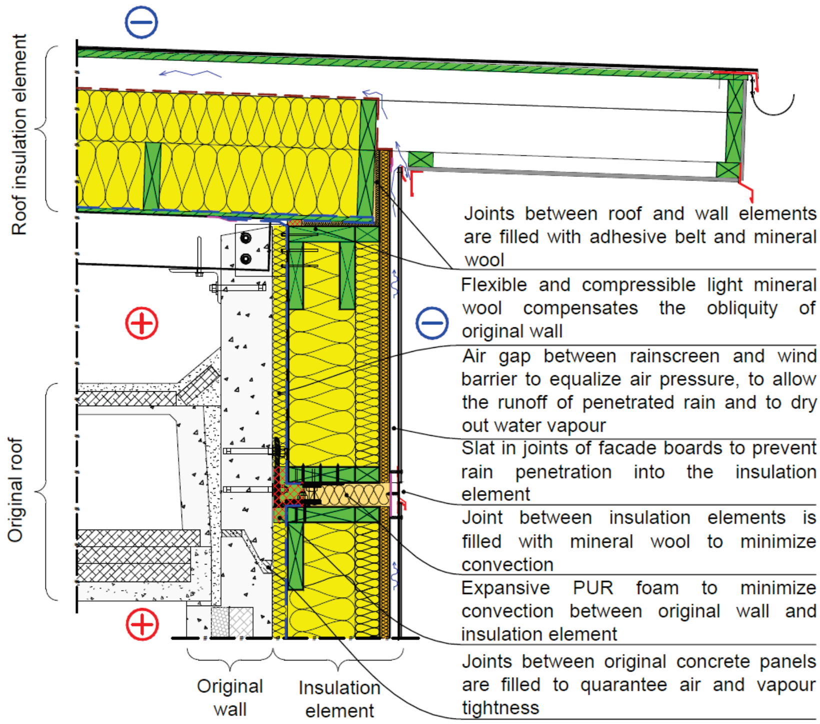


Figure 4.18 Final design solution of the PCLP pilot building with wall and roof connection, vertical section. Greyscale – original PCLP; coloured – prefabricated timber frame insulation elements. Scale 1 : 20. Adapted from publication IV.

Based on the final design of wall type 1 (see Figure 4.17), the prototypes of the prefabricated elements were produced and analysed with the team of constructors and producers of the elements to find possible weaknesses in the design of the structure and develop the production of elements. The main questions addressed were appropriate design, sealing and tightening of joints, placement and mounting of hanging brackets and embedding ventilation ducts into the elements.

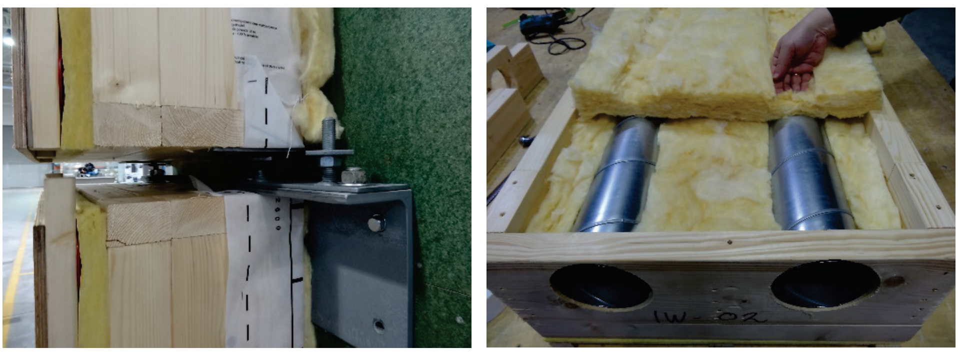


Figure 4.19 Prototyping of the prefabricated elements in 2016. Consideration of joint and hanging bracket (left). Trial of placing insulation around embedded ventilation ducts in the element (right).

4.4.4 Production and installation of prefabricated timber frame insulation elements

All material layers, window blocks and facade boarding with accessories (water slats, sealings, corner profiles etc.) were installed in the factory and protected with plastic foil from weather damage during transportation and on the building site. The elements were produced and delivered to the building site by a strict schedule to spare the storing space on the building site and save on the use of cranes. The timber frame insulation elements were produced, delivered and installed on the pilot building by the producer of the elements and modules AS Matek.

Figure 4.20 Production of elements at the factory of AS Matek in 2017. Preparation of timber framing for insulation (top left), fixing of MW wind barrier boards and ventilated air gap battens (top right), mounting of facade boards (bottom left) and windows (bottom right).

The shortage of places for new ventilation ducts in apartments was solved in the design of this project with the integration of preheated air supply ducts into prefabricated elements (see Figure 4.17, bottom and Figure 4.21). To minimise connections of ventilation pipes on the building site, the elements with embedded ventilation ducts were designed to be installed in a vertical direction while all other elements were designed to cover the existing envelope in a horizontal direction (see Figure 4.28, right). During the workshops and working sessions at the factory, improvements and adjustments of the initial design of joints and connections were made to guarantee better waterproofness and airtightness. Taping and sealing without gaps around windows from inside and outside were strictly followed (see Figure 4.22).

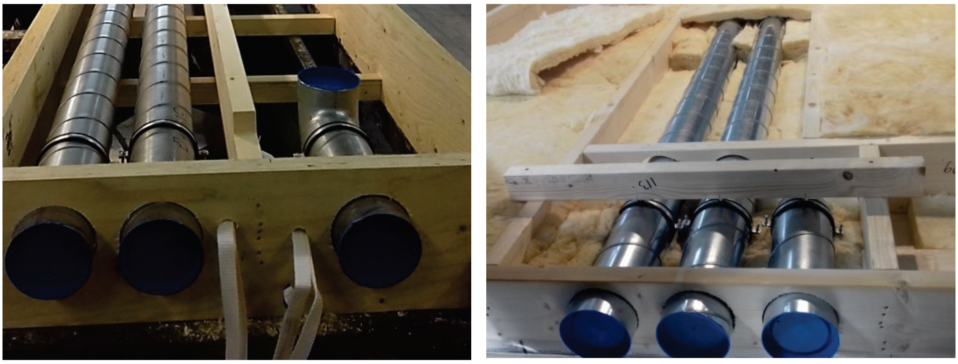


Figure 4.21 Ventilation ducts embedded into the prefabricated wall elements on the factory production line (2017).

Figure 4.22 Wall elements are prepared for the installation of windows at the factory (above). Continuous sealing around installed window frames from inside (bottom left) and outside (bottom right) (2017).

After the taping, EPDM sealing and steel stripes were fixed onto the framing at the factory to protect layers beneath (see Figure 4.23, top). The initially designed connections of the drip mould, window sides and boarding were revised to withstand WDR loads (see Figure 4.23, bottom). To guarantee the airtightness of the structures and avoid time-consuming tightening of the original envelope, the airtightness of the building was ensured with a sealed air and vapour barrier layer on the element at the first step at the factory (see Figure 4.24) and finally sealed on the building site after the installation of elements (see Figure 4.26).

Figure 4.23 *EPDM sealing and protecting steel strip on the window side (top left) and on the battens of the ventilated air gap (top right). Initially designed drip mould (bottom left) and revised final solution (bottom right) (2017).*

Figure 4.24 *All joints and connections were properly sealed at the factory from interior side (left) and from exterior side, including penetrations of ventilation ducts (right) (2017).*

On the building site, intersections between installed elements and around hanging brackets were filled with expansive polyurethane (PUR) foam (see Figure 4.25, left). To avoid thermal bridges and to minimise the impact of air leakage and convection, all joints between elements were filled with mineral wool bands (see Figure 4.25, right).

Figure 4.25 Joints between elements were filled with PUR foam (left) and mineral wool bands to avoid thermal bridges and minimise the convection (2017).

Filled joints were covered with a self-adhesive sealant to close the gaps between wind barrier boards (see Figure 4.26, left). Vertical steel strips under the facade boards and horizontal joints closed with drip moulds prevent WDR overflow to the structure beneath (see Figure 4.26, right).

Figure 4.26 Self-adhesive sealant was used in the joints between the elements (left). Joints of facade boards were closed with steel strips and drip moulds preventing WDR overflow to the structure beneath (right) (2017).

The concrete slabs (barriers) in front of open loggias were taken down and loggias were closed from the exterior side with prefabricated elements (see Figure 4.17, wall type 2 and Figure 4.28, left). With that, each apartment gained extra space in the living room or kitchen, depending on the apartment plan. The designed thermal transmittance of wall type 2, in case of which the open loggias were closed with elements covered from the interior side with gypsum board, $U_{\mathrm{wall2}} \leq 0.12$ W/(m^2·K). Triple glazed windows with low emissivity coating, $U_{\mathrm{window}} \leq 0.80$ W/(m^2·K), were installed into the elements. In the wall element with the dimensions ≈ 2.7 m $\times$ 9 m are up to three preinstalled in factory windows with all accessories mounted (tightened joints, window plates, sealing tapes etc.). The old windows were removed from the original walls after the whole insulation system was installed. This allows performing works with minimal disturbance of tenants and continuing renovation works during the cold season as well. Continuous airtight sealing was adhered to the dust-free joint of old window sides on the concrete panel and the new window block (see Figure 4.27).

Figure 4.27 Old window block is removed (left). New window block in the prefabricated element and airtight sealing around the sides of the window opening (right) (2017).

Figure 4.28 Open loggias are ready for prefabricated elements to be installed (top left). Lifting of a vertical wall element with embedded ventilation ducts (bottom left). Installation of the prefabricated timber frame insulation elements on the pilot building (right) (2017).

Figure 4.29 PCLP apartment building after renovation (Rudi 2017).

4.5 Commissioning of moisture safety

4.5.1 Design process

Requirements for moisture safety were described in the design task as follows:

- The building envelope must be designed and constructed in such a way as to ensure the moisture safety of the building;
- The hygrothermal performance of the building envelope is covered by standards (EN 15026:2007, EN ISO 13788:2012);
- Dampness, mould damage and the degradation of materials should be avoided;
- The design must ensure that material-based critical humidity is not exceeded (i.e. humidity of the material, exceeding of which may cause moisture damage including the deterioration of surface, microbial growth or degradation of material);
- The critical humidity depends on the material and is determined by the manufacturer's data. In the absence of the manufacturer's data, relative humidity of 75% and a corresponding moisture content of the material are used as critical moisture limit values.

The design requirements for moisture safety were adequate in general and were implemented to project documentation where appropriate. The only problem was with the determination of the water vapour permeability of the air and vapour barrier. The designer's first choice (PE-foil as a typical solution for timber frame exterior walls) was acceptable according to EN ISO 13788 methodology. Nevertheless, the PE-foil as the air and vapour barrier turned out to be too vapour-tight to allow the dry-out of constructional moisture from the original PCLP wall and could have caused mould growth in the MW and timber parts. Dynamic hygrothermal simulation (according to EN 15026) was unknown to the designer. The developer's moisture experts conducted the required simulations (see publications II and III) and determined the requirements for the IMC of the original PCLP wall before the installation of elements ($w \leq 110$ kg/m^3) and water vapour permeability of the air and vapour barrier layer (0.2 m at RH 85% $\leq S_d \leq$ 5 m at RH 20%) for wall type 1, i.e. the original PCLP wall with prefabricated insulation elements (see Figure 4.17). PE-foil as the air and vapour barrier was used with no problems on wall type 2, where prefabricated insulation elements were directly connected to the indoor conditions, i.e. on formerly opened loggias that became a part of indoor premises after the renovation of the pilot building.

4.5.2 Construction process

Requirements for moisture safety in the construction process were described in the design documentation:

- Special attention has to be paid to the protection of products against moisture (weather protective and sealed foils, transport pallets under the unloaded elements on site);
- The surfaces to be covered have to be dry and free of water, ice or snow;
- The order of work and weather protection should be planned in a way ensuring that rainwater does not get into the structures;
- In case of the interruption of work, temporary weather protection (e.g. tarpaulins) have to be used in a way that prevents the wetting of the insulation and timber details due to rain and flood water;
- The timber materials supplied to the construction site have to be protected from the weather;
- The moisture content of the installed timber should stay below 15% (16–1% of measurement accuracy);
- Timber structures have to be separated from concrete structures by a damp- and waterproof material layer.

Several moisture safety setbacks were recorded during the construction process. The contractor was unsuccessful in many aspects of the designed requirements. Because of the delays in the work schedule due to the slower mounting of the brackets for elements and installation of the first insulation elements, the contractor did not always respect the required weather protection criteria.

Even if the preliminary facade protection was used during rainy days, some parts of the facade were still affected by WDR (see the darker area between window openings in Figure 4.30, top). In the worst-case scenario, rainwater flowed inside the element or between the element and the original PCLP wall (see Figure 4.30, bottom) and the sub-contractor was forced to dry it out before the next phases of the renovation process.

The designed for the pilot building prefabricated roof insulation elements were planned to overhang the facade and it was planned to use a crane to lift the wall and roof elements. Therefore, it was not possible to install the roof elements before the wall elements, leading to the sides of mounted wall elements remaining open and vulnerable to rain for some time (see Figure 4.30, top). After pointing out some critical mistakes, tarpaulins protecting from rain were used during the installation of the prefabricated elements. Leakages found were dried out mechanically before the final closure of the envelope.

Figure 4.30 Installation of prefabricated insulation elements with insufficient moisture protection (top). Rainwater has flowed inside the element and between the element and the original PCLP wall (bottom) (2017).

4.6 Post-renovation analysis of prefabricated timber frame insulation elements for deep energy renovation

4.6.1 Measured and modelled hygrothermal performance

At the pilot building, indoor and outdoor relative humidity (RH_i, RH_e) and temperature (t_i, t_e) were measured and in the analysed points relative humidity (*RH*4, *RH*6) and temperature (*t*4, *t*6) were measured and calculated during and after the renovation. See Figure 4.31, Figure 4.32 and measurement points in Figure 4.17 (top).

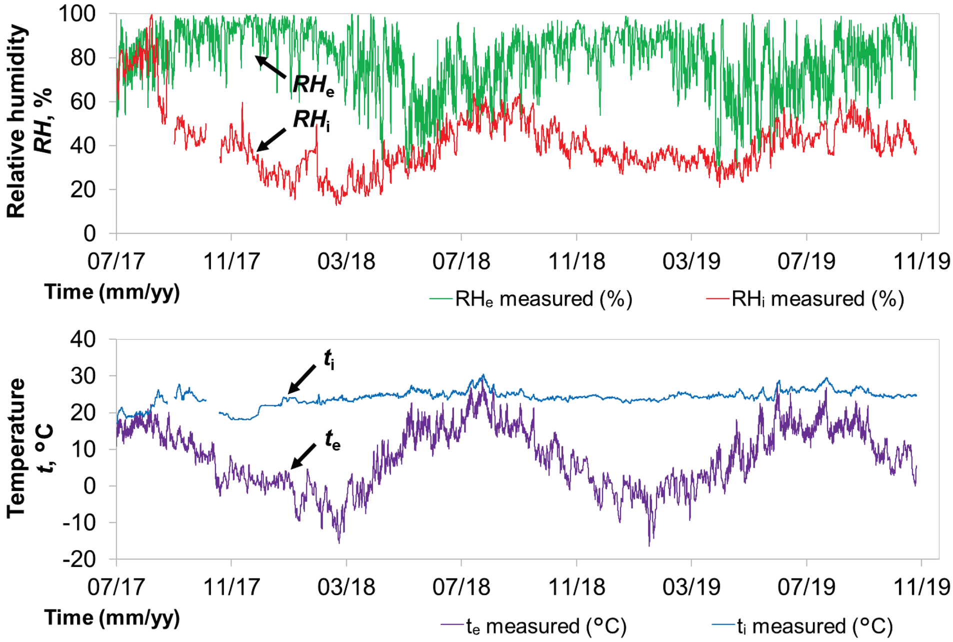


Figure 4.31 *Measured indoor and outdoor relative humidity (RH_i, RH_e) and temperature (t_i, t_e). See Figure 4.17 (top) for the measurement points. Adapted from publication V.*

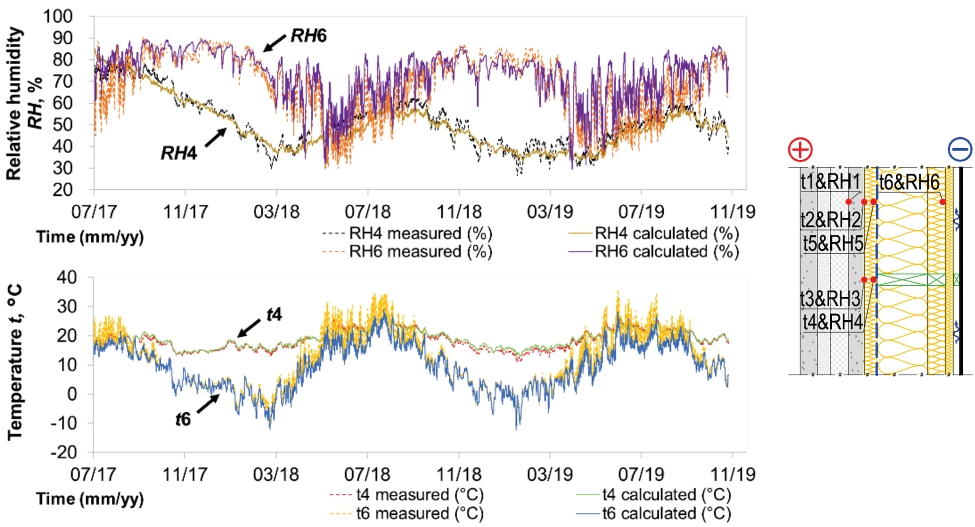


Figure 4.32 *Measured and calculated relative humidity (RH4, RH6) and temperature (t4, t6). See Figure 4.17 (top) for the measurement points. Adapted from publication V.*

Comparison of the long-term measurements and simulations with the calibrated model in critical points between the timber frame element and the MW buffer layer (see Figure 4.17 (top), point t4&RH4) and between the wind barrier layer and the insulation of the timber frame element (see Figure 4.17 (top), point t6&RH6) showed good agreement of the measured and modelled values.

4.6.2 Analysis of moisture dry-out

Figure 4.33 shows the intervals from the installation of elements up to the end of the year 2019 along with the calculated MC at different depths of the PCLP. See Figure 4.17 (top), detail 1.1 for points A, B, C. The average MC levels of the PCLP exterior slab are shown in Figure 4.33 (see bar chart).

Critical MC ($w = 110$ kg/m^3) was never exceeded during the installation of the prefabricated elements or after the start of use of the building. Moisture redistribution in different seasons and at different depths of the PCLP is an important factor to follow. In spring and summer periods the external layer (see Figure 4.33, point A) started to dry out but in the deeper parts (points B and C) the MC was much higher. This must be considered if superficial measurements from the exterior thin layer are taken on the building site. The overall MC that dried out from the concrete wall, starting from the installation in May 2017 to the July of 2019, was about 41 kg/m^3. The quantity of dried out moisture during the first 6 months was 23 kg/m^3 (i.e. 1.4 kg/m^2 of 60 mm concrete panel) and during the next 12 months it was 12 kg/m^3 (0.7 kg/m^2 of 60 mm concrete panel). Starting from July–August 2019 the MC stayed in the range of 30 kg/m^3 without any conspicuous fluctuations. This means that 2 years after insulation elements had been installed onto the exterior side of the original PCLP the MC level of PCLP had reached the equilibrium state.

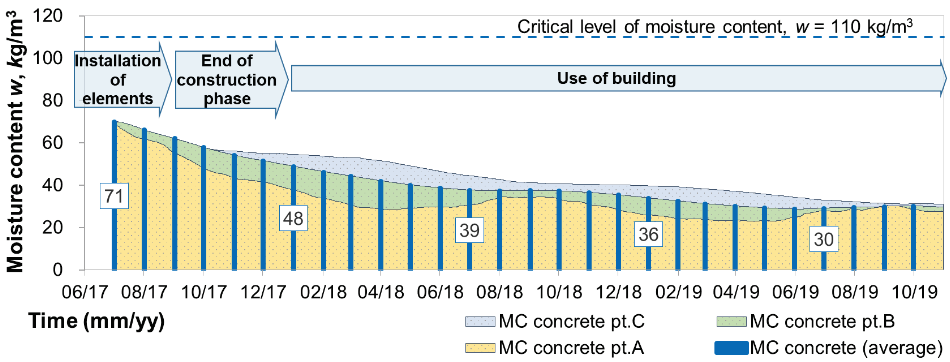


Figure 4.33 Moisture dry-out from the PCLP wall insulated with prefabricated timber frame insulation elements. See Figure 4.17 (top), detail 1.1 for the analysed points A, B, C. Reproduced from publication V.

4.6.3 Analysis of mould growth risk

The results of the calculations with the mould growth model in the measured points of the PCLP pilot building showed that the critical *RH* level was exceeded for a short term in warm seasons (see Figure 4.34, left) and the mould index remained below the critical level ($M < 1$) (see Figure 4.34, right).

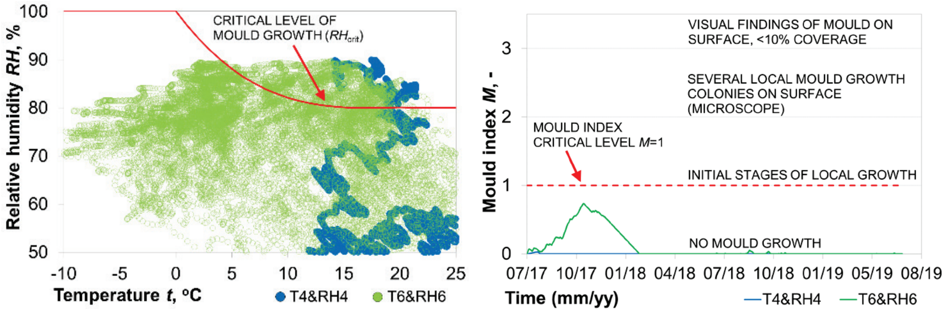


Figure 4.34 Temperature (t) and relative humidity (RH) in the analysed points compared to the critical level of mould growth (left). Calculated mould index M in the analysed points (right). See Figure 4.17 (top) for the analysed points. Reproduced from publication V.

4.6.4 Post-installation observations and guidelines

Answers to interviews with production companies, installation contractors, as well observations of analysis of renovation prospects with prefabricated elements, point out the most relevant problems and give guidelines for future research and development.

Accuracy of predesign and pre-installation measurements (e.g. geodesy, point-cloud and 3D model) are crucial for a streamlined production and installation of elements because these reveal all possible deviations of openings and roughness of the original wall surface in all directions. The design of and construction works at the pilot building verified the importance of precise data about envelope roughness because the surface deviations both in vertical and horizontal directions were up to ±50 mm. Therefore, designed hanging brackets for elements should have an adjustable clearance allowing regulation of the elements in all directions during the installation to minimise the risk of time-consuming remounting of brackets in case of measurement inaccuracies.

The buffering layer has to be a light and compressible (flexible) material (e.g. MW, $\rho < 20$ kg/m^3) allowing the element to be safely pressed towards the uneven original surface and to be fixed to the load-bearing brackets while it hangs on the crane hooks and workers are standing in the high forklift basket. On the pilot building it was clearly seen that in some places the installers had quite some difficulties with pressing the element tightly to the original surface because of the variations of the surface level. Lighter MW as the buffering layer and brackets with greater adjustment clearance could help out.

Water and air tightness of horizontal joists between the elements was difficult and time-consuming to achieve as the elements are supported on a wall by each intermediate floor. Fastening of elements in the vertical direction is safer and allows designing and finishing larger gaps between elements. But in this case, the mistakes from construction tolerances are transmitted and large differences in sizes can occur because of the existing wall roughness and irregularity.

Use of a traverse for lifting long and heavy elements by crane helps to avoid bending out or breaking an element but it can be impeded if the building has roof eaves stepping out of the wall perimeter. In that case, a forklift with a special lifting and supporting frame could be a solution. Or else, the solution could be to remove part of the roof and eaves temporarily. However, this is again an additional risk of rainwater overflow and moisture damage during construction works and needs an extra investment to prepare and remount the roofing.

Use of continual protective tarpaulins or tents on the existing envelope is obstructed because the crane or forklift must have access to wall surfaces to lift and fix the elements. Prefabricated elements must be packed to a protective foil firmly already at the factory to ensure their safe transport and installation without moisture impairments. The protective foil has to be removed only after the element is installed.

These are the important aspects of moisture safety and building technology that have to be analysed, explained and agreed in the contracting phase and controlled by a moisture safety expert and the owner's surveillance engineer during the installation works.

4.7 Material combinations and energy and cost calculations of prefabricated timber frame insulation elements for deep energy renovation

4.7.1 Hygrothermal performance

Mould index *M* was calculated in critical points (see Figure 3.16) for all sets studied. Results are shown in in Table 4.2 and Table 4.3 where the mould index is given at different initial moisture content levels of the original PCLP wall with installed prefabricated insulation elements. Risks of mould formation are categorised in Table 4.2 and Table 4.3 by colours:

- Green – no mould growth risk, $M < 1$;
- Yellow – minor mould growth risk, $1 \leq M < 2$, i.e. small amounts of mould on surface (microscope), initial stage of local growth;
- Red – high mould growth risk, $M \geq 2$, i.e. several local mould growth colonies on surface (microscope).

The use of the following wind barrier materials is illustrated in Table 4.2 and Table 4.3:

- D1 – Sheathing membrane ~0.2 mm (S_d = 0.015 m at *RH* 85%);
- D2 – Gypsum board wind barrier 9 mm + sheathing membrane D1;
- D3 – Fibre cement board 9 mm;
- D4 – Wood fibreboard 22 mm;
- D5 – MW wind barrier board 30 mm with special facing.

Full information about materials used in this chapter is presented in Table 3.2 and in publication VI, Table 1.

Table 4.2 Mould index (M) for wall constructions with MW at the IMC of the original PCLP wall w = 85 kg/m³ (u = 3.7%), w = 95 kg/m³ (u = 4.1%), w = 110 kg/m³ (u = 4.7%).

Wind barrier layer	Air and vapour barrier	Mould index *M* (green, yellow, red) with different frame thicknesses at the most critical points (4 or 6) *								
		120 mm			145 mm			195 mm		
		IMC of the PCLP wall (kg/m^3)								
		85	95	110	85	95	110	85	95	110
D1	B1	4	4	4	4	4	4	4	4	4
D2		4	4	4	4	4	4	4	4	4
D3	0.2 m ≤ S_d ≤ 5 m	4	4	4	4	4	4	4	4	4
D4		4	4	4	4	4	4	4	4	4
D5		4	4	4	4	4	4	4	4	4
D1	B2	6	6	6	6	6	6	6	6	6
D2		6	6	6	6	6	6	6	6	6
D3	Without vapour barrier	4	4	4	4	4	4	4	4	4
D4		6	6	6	6	6	6	6	6	6
D5		4	4	4	4	4	4	4	4	4
D1		4	4	4	4	4	4	4	4	4
D2	B3	4	4	4	4	4	4	4	4	4
D3		4	4	4	4	4	4	4	4	4
D4	S_d ≥ 50 m	4	4	4	4	4	4	4	4	4
D5		4	4	4	4	4	4	4	4	4

* Numbers 4 and 6 indicate the most critical points (see Figure 3.16):

- Point 4 – between original wall and air and vapour barrier layer;
- Point 6 – between wind barrier and insulation layer of prefabricated element.

no mould growth risk, *M* < 1

minor mould growth risk, 1 ≤ *M* < 2

high mould growth risk, *M* ≥ 2

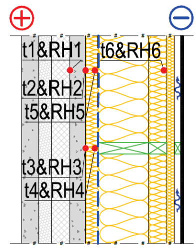
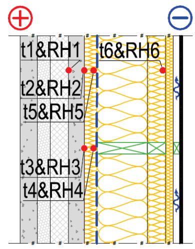


Table 4.3 Mould index (M) for wall constructions with CW at the IMC of the original PCLP wall w = 85 kg/m³ (u = 3.7%), w = 95 kg/m³ (u = 4.1%), w = 110 kg/m³ (u = 4.7%).

Wind barrier layer	Air and vapour barrier	Mould index *M* (green, yellow, red) with different frame thicknesses at the most critical points (4 or 6) *								
		120 mm			145 mm			195 mm		
		IMC of the PCLP wall (kg/m³)								
		85	95	110	85	95	110	85	95	110
D1	B1	4	4	4	4	4	4	4	4	4
D2		4	4	4	4	4	4	4	4	4
D3	0.2 m ≤ S_d ≤ 5 m	4	4	4	4	4	4	4	4	4
D4		4	4	4	4	4	4	4	4	4
D5		4	4	4	4	4	4	4	4	4
D1	B2	6	6	6	6	6	6	6	6	6
D2		6	6	6	6	6	6	6	6	6
D3	Without vapour barrier	4	4	4	4	4	4	4	4	4
D4		6	6	6	6	6	6	6	6	6
D5		4	4	4	4	4	4	4	4	4
D1		4	4	4	4	4	4	4	4	4
D2	B3	4	4	4	4	4	4	4	4	4
D3		4	4	4	4	4	4	4	4	4
D4	S_d ≥ 50 m	4	4	4	4	4	4	4	4	4
D5		4	4	4	4	4	4	4	4	4

* Numbers 4 and 6 indicate the most critical points (see Figure 3.16):

- Point 4 – between original wall and air and vapour barrier layer;
- Point 6 – between wind barrier and insulation layer of prefabricated element.



- no mould growth risk, $M < 1$ (green)
- minor mould growth risk, $1 \le M < 2$ (yellow)
- high mould growth risk, $M \ge 2$ (red)

Results of calculations of mould indexes (i.e. mould growth risk) in Table 4.2 and Table 4.3 show that all analysed combinations with vapour barrier with varying vapour resistance (see Table 4.2 and Table 4.3, pos. B1, and in publication VI, Table 1) or without air and vapour barrier layer (pos. B2) are below the critical limit (M = 2) of mould growth risk. Minor mould growth risk ($1 \le M < 2$) is in constructions insulated with MW when a sheathing membrane (pos. D1) or gypsum board with a sheathing membrane (pos. D2) as the wind barrier layer was applied. Also, with fibre cement board (pos. D3) and wood fibreboard (pos. D4) as wind barrier layers on higher insulation thicknesses and with the initial moisture content (IMC) of the original concrete wall $w \ge 95$ kg/m³ minor mould growth risk was determined. With CW some mould growth risks are noticeable with wind barriers pos. D1, pos. D2 and pos. D3 when the IMC of the original concrete wall $w \ge 95$ kg/m³ and in case of higher thicknesses of insulation without an air and vapour barrier layer (pos. B2). All analysed combinations with PE-foil as the air and vapour barrier layer (pos. B3) are beyond the critical limit of mould growth risk ($M \geq 2$) and therefore cannot be used in these structures. From the perspective of hygrothermal performance, MW board of ≥ 30 mm thickness with a special wind barrier facing is the best material for wind barriers.

4.7.2 Energy performance

The annual energy use of the reference apartment building (see Figure 2.1, left) with a total heated area of 2968 m^2 was calculated with different sets of the external wall insulation elements following criteria for renovation measures of the grant scheme (RT I, 09.04.2019). The calculations were based on the IDA ICE simulation results for the reference building. The variation of total delivered energy to the renovated building with well insulated external walls is up to ±2%, see Table 4.4. The variation is relatively small because the building envelope is already well insulated and thus, energy for space heating is one of the smallest components of energy use.

Table 4.4 Influence of thermal transmittance of external walls on the use of delivered energy by the apartment building.

Thermal transmittance of the external wall U_c, W/(m²·K) *	Delivered energy, kWh/(m²·a)						
	Heat			Electricity			Total
	Space heating	MVHR	DHW	Equip-ment	Fans, pumps	Light-ing	
0.22	14.0	16.9	33.3	22.5	10.5	7.0	104
0.21	13.7	16.9	33.3	22.5	10.5	7.0	104
0.20	13.4	16.8	33.3	22.5	10.5	7.0	104
0.19	13.1	16.8	33.3	22.5	10.5	7.0	103
0.18	12.8	16.7	33.3	22.5	10.5	7.0	103
0.17	12.5	16.6	33.3	22.5	10.5	7.0	103
0.16	12.2	16.6	33.3	22.5	10.5	7.0	102
0.15	11.9	16.5	33.3	22.5	10.5	7.0	102
0.14	11.7	16.5	33.3	22.5	10.5	7.0	101
0.13	11.4	16.4	33.3	22.5	10.5	7.0	101

* Thermal transmittance is calculated with existing original wall construction ($R_{exist.wall}$ = 1 m²·K/W).

The primary energy use depends mostly on the efficiency of district heating (the most typical heat source for apartment buildings in Estonia). After the renovation and with efficient district heating (i.e. $CF_{efficient\ district\ heating}$ = 0.65) the apartment building fulfils the nZEB requirements for the new buildings (RT I, 13.12.2018) and with the common district heating (i.e. $CF_{district\ heating}$ = 0.9) the nZEB requirements for major renovation (i.e. current energy performance certificate level 'C'). The results obtained contain a reasonable reserve for unforeseen energy use (e.g. user's influence), see Table 4.5.

Table 4.5 Influence of the heat source on the use of primary energy by the apartment building.

Thermal transmittance of the external wall U_c, W/(m²·K) *	Primary energy, kWh/(m²·a)					
	Efficient district heating			Common district heating		
	Heat (CF=0.65)	Electricity (CF=2.0)	Total	Heat (CF=0.9)	Electricity (CF=2.0)	Total
0.22	41.8	80.1	122	57.8	80.1	138
0.21	41.5	80.1	122	57.5	80.1	138
0.20	41.3	80.1	121	57.2	80.1	137
0.19	41.1	80.1	121	56.9	80.1	137
0.18	40.8	80.1	121	56.5	80.1	137
0.17	40.6	80.1	121	56.2	80.1	136
0.16	40.4	80.1	120	55.9	80.1	136
0.15	40.2	80.1	120	55.6	80.1	136
0.14	39.9	80.1	120	55.3	80.1	135
0.13	39.7	80.1	120	55.0	80.1	135

* Thermal transmittance is calculated with existing original wall construction ($R_{exist.wall}$ = 1 m²·K/W).

4.7.3 Cost analysis

The unit prices of prefabricated insulation elements with different wind barrier layers (see Table 4.6) are given without the prices of facade system materials and include production, transport and installation costs.

Table 4.6 Unit prices of prefabricated timber frame insulation elements with different insulation (MW, CW) and wind barrier materials (D1 to D5) without facade materials. See publication VI, Table 1 for description of layers D1…D5.

Wind barrier layer	Unit price of element, €/m² (frame thickness)					
	120 mm		145 mm		195 mm	
	MW	CW	MW	CW	MW	CW
D1	88	85	90	87	96	93
D2	93	90	95	92	101	98
D3	96	93	98	95	105	102
D4	98	95	100	97	107	104
D5	100	97	102	99	108	105

The cost of facade systems (see Table 4.7) is given separately with maintenance cost and maintenance interval for each facade material type (per 1 m² of facade). The total initial cost (production, transport, installation) of insulation elements varies between 101 and 164 €/m². The selection of the facade system has the highest influence on the total initial cost: ±13–15%. The selection of the wind barrier influences the total initial cost by ±5–6% and the insulation material by ±1%.

Table 4.7 Unit prices, maintenance cost and intervals of maintenance of facade systems of the prefabricated elements. See publication VI, Table 1 for description of layers F1...F6.

Facade system	Unit price of facade, €/m^2	Maintenance cost, €/m^2	Maintenance interval, years
F1	18	15	15
F2	22	5	15
F3	35	15	15
F4	54	5	25
F5	55	5	25
F6	56	15	20

As the facade cladding does not influence essentially the mould growth risk in the critical points, the cost difference was compared without the facade system. As the influence of insulation materials cost (MW or CW) was very small, Figure 4.35 presents the results of sets with MW insulation only. Results are given as the cost difference compared to the insulation element with 145 mm framing with 50 mm buffering insulation layer (see Figure 3.16, pos. A) + air and vapour barrier (pos. B) + MW insulation (pos. C) + 30 mm MW wind barrier (pos. D) + wooden boarding as facade system (pos. E + pos. F). By combining moisture safety (Table 4.2) and total cost (Table 4.6) we can see that decreasing the total cost increases the risk of mould growth. Insulation elements with some mould growth risk ($1 \le M < 2$) were cheaper than solutions without mould growth ($M < 1$).

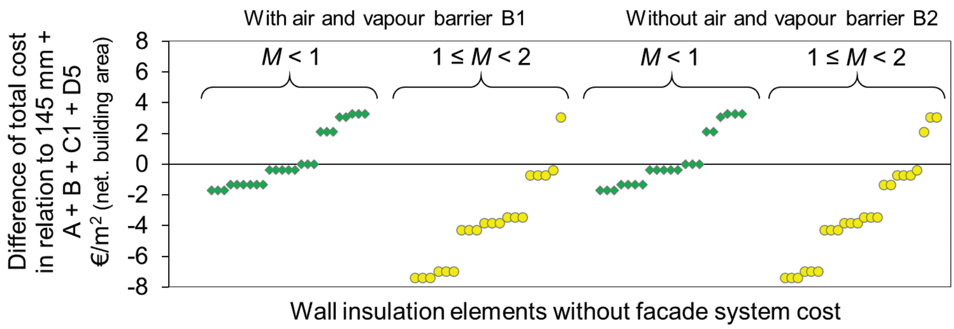


Figure 4.35 Influence of changing the total cost on the risk of mould growth without the contribution of facade systems to the cost of prefabricated element. Reproduced from publication VI.

5 Discussion

5.1 Parameters influencing the hygrothermal performance of highly insulated timber frame structures

The performed hygrothermal simulations showed that a careful selection of materials makes it possible to design timber frame exterior structures that are moisture safe and provide low thermal transmittance. The hygrothermal performance of the timber frame exterior wall was found to depend most of all on the thermal resistance of the wind barrier and the water vapour permeability of the wind barrier and the vapour barrier. This is also described by other authors from cold climates (Vinha 2007, Gullbrekken et al. 2015). When the thermal transmittance of the timber frame exterior wall is decreased only by increasing the thickness of insulation, the risk of mould growth will increase. The increase of mould growth risk in the course of the lowering of the thermal transmittance is lower for some wind barriers; these materials can be described by higher thermal resistance and water vapour permeability.

Comparison of mineral wool (MW) and cellulose wool (CW) as insulation materials revealed that the structure with CW had lower mould growth risk than the structure with MW if the other materials of the envelope remained unchanged (see Figure 4.3 and Figure 4.4). The current study shows that in the cold and humid climate conditions, an increase of insulation thickness without any changes of other material layers in the structure has an adverse effect on the hygrothermal performance of the highly insulated building envelope. Thicker insulation (i.e. larger volume of material in the envelope) may contain more built-in moisture, which needs to dry out after the construction process. A smaller heat flow slows down the dry-out rate of moisture, which could be a factor causing a highly insulated wall to become more sensitive to moisture damage. Vinha et al. (2001) tested the moisture behaviour of structures with CW and concluded that the use of cellulose insulation slows down the increase in relative humidity (*RH*) values behind the windshield during the autumn and winter periods. Our study also shows this. It is mainly due to higher moisture storage and capillary moisture transfer properties of cellulose insulation. Therefore, the capillary transport properties and moisture capacity of wood and paper-based materials should be exactly known.

Parameter analysis (thickness, water vapour permeability and thermal conductivity) in the comparison of MW and CW insulation indicated that the moisture buffering and dry-out capability of the insulation material have the strongest influence on the *RH* between the insulation and the wind barrier layer. Higher moisture diffusivity allows inward moisture dry-out and reallocation by capillary forces. Higher moisture storage helps to survive shorter periods with high hygrothermal loads. Andersen et al. (2002) showed a tendency that the moisture content (MC) behind a wind barrier, measured in the north-facing facade element with MW (stone wool), is higher than in the facade element insulated with CW. Nevertheless, when the insulation with a high moisture capacity has become wet, its drying-out period is longer than for materials with low moisture storage properties. Hence, higher moisture storage properties have both positive and negative aspects that should be considered in the design of the structures.

The analysis in this study showed the walls with non-hygroscopic insulation and wind barrier layers with low thermal transmittance and water vapour permeability to be more sensitive to mould growth. Similarly, we agree with researchers (Langmans et al. 2012) who have pointed out that a low water vapour permeability of the external (i.e. wind barrier) layer of the envelope leads to an increased risk of mould growth and interstitial condensation against the upper position of the exterior sheathing in winter conditions.

Analysis confirmed that the hygrothermal performance of the timber frame exterior wall strongly depends also on the material properties of the wind barrier, where thermal resistance and water vapour permeability are the most important parameters. Higher water vapour permeability of the wind barrier allows the moisture to be dried out from the wall structure more efficiently. Higher thermal resistance increases the temperature between the insulation and the wind barrier and thus the *RH* decreases respectively. If the initially designed wind barrier is replaced with another material (i.e. with lower thermal resistance and water vapour permeability), the hygrothermal performance of the whole structure may degrade (see Figure 4.5). This situation may occur during construction works when the initially designed wind barrier is changed to decrease the price or due to the lack of specific materials but without the evaluation of hygrothermal risks. The thermal resistance of dense and relatively vapour-tight wind barriers (e.g. gypsum board or oriented strand board (OSB) with R = 0.05–0.10 m^2·K/W, S_d > 1 m) is not as high as the needed minimum for wind barrier layers in order to maintain mould risks in critical points of highly insulated structures below the secure limit (M < 1). Even the thermal resistance of the 22 mm wood fibreboard (R = 0.44 m^2·K/W) is not sufficient when the air and vapour barrier layer's vapour resistance S_d < 5 m. In these cases, the *RH* behind the wind barrier has to be kept lower with an additional insulation layer (e.g. MW) on the external side of the wind barrier, where depending on wind barrier properties, the thickness of the additional insulation needed is up to 100 mm. However, this is not a cost-efficient and technologically reasonable option. If such wind barriers with higher density and vapour resistance (e.g. wood fibreboard, gypsum board, OSB or similar ones) are required, it is recommended that these products be used in case of lower thermal transmittances of the building envelope (U ≤ 0.17 W/(m^2·K)) only after preliminary hygrothermal analysis because of the high mould formation risk.

Favourable solutions in that case will be wind barrier materials with higher thermal resistance and water vapour permeability and where the air and vapour barrier layer is included on the inner side. Glass et al. (2015) studied moisture performance in energy efficient buildings and came to the conclusion that the combination of high interior humidity and high water vapour permeability of the interior gypsum board leads to significant moisture accumulation in OSB (wind barrier) sheathing during winter in walls without a vapour retarder but in contrast, wintertime moisture accumulation is not significant with an interior kraft vapour retarder. To ensure moisture safety of a highly insulated envelope in a cold climate, in most cases thermal resistance R > 0.4 m^2·K/W and vapour diffusion resistance S_d < 0.05 m of the wind barrier layer is needed for walls with non-hygroscopic insulation and a proper air and vapour barrier layer (S_d > 1 m) should be included on the inner side of the envelope. The same limits are also described in an earlier research (Mundt-Petersen 2015), but our estimations concerning vapour resistance properties of the vapour barrier layer are even stricter (see publication I, Table 3).

A good exception is semi-rigid MW wind barrier board, which showed the best hygrothermal performance and very low mould growth risk because of its high thermal resistance and water vapour permeability (R = 0.80 m^2·K/W, S_d = 0.04 m). However, its inability to serve as a stiffening layer of framing (caused by its softness and elasticity compared to other analysed dense wind barrier boards, e.g. gypsum board or OSB) makes it to be often considered as a second choice from the cost-effectiveness point of view. Producers of prefabricated elements are obliged to consider in addition to hygrothermal properties the simplicity and cost of the whole solution. Installation of MW wind barrier board can be more time-consuming, it needs distant spacers to be mounted (as an additional working operation) to maintain its designed thickness under the load of battens from the ventilated air gap and the facade covering it (see Figure 3.1, pos. 1–3).

The hygrothermal analysis of this study is based on a cold climate. Field measurements have shown (Kalamees 2006c, Geving and Holme 2011, Arumägi et al. 2015) that here typical household activities and ventilation cause higher water vapour content indoors than outdoors. Therefore, the water vapour diffusion and convection are directed from indoors to outdoors and usually the most critical zone appears between the wind barrier and the insulation layer (Vinha 2014) and the vapour barrier layer keeps the water vapour from indoors off the installed structure. For milder Central-European countries or climates, where the movement of moisture in structures is in the opposite direction, the risk of condensation is lower and the influence of the change of thermal transmittance on the moisture safety of the structures should be investigated separately. Hence, to perform analysis, design and cost estimations, the properties of materials with the most critical impact on hygrothermal performance need to be described in the structural and/or constructional project documentation and preliminary calculations should be made to guarantee moisture safety.

5.2 Moisture content and the dry-out capability of the PCLP wall

Long-term (1970–2012) analysis of typified PCLP elements indicated that the highest constructional moisture content (MC) is in the middle and inner zones of the exterior 60 mm thick concrete slab and the most critical to hygrothermal performance months are November, December and January. This could be explained with the moisture dry-out, diffusion and absorption phenomena: the weather (wind and solar radiation) contributes to faster dry-out of moisture in the outer layer of the external wall in the warmer seasons. But at the end of the year and during colder periods with heavy rains, the moisture load is higher, and moisture dry-out times are longer. Therefore, the moisture will accumulate and redistribute inside the structure. The calculations showed that during autumn and winter periods, the exterior concrete slab may stay close to the full saturation state and the wall will dry out only in March–April. Nik et al. (2015) studied future scenarios, and according to their research results, higher amounts of moisture will accumulate in walls in the future, caused predominantly by the changing weather. Longer periods of a high MC will contribute also to the activation of corrosion processes and the risk of moisture growth will rise.

Analysis of MC fluctuations and decrease verified the previous finding in our studies that the most critical are the last quarter and the first months of the year, when the MC in the concrete slab is the highest. The moisture dry-out from the concrete structure after a rainfall is in the range 5–20 kg/m^3 in 10 consecutive days without precipitation, depending on the seasonal conditions and initial moisture content (IMC). Therefore, because of the high variability of MC levels and drying out times, it is essential to keep hygrothermal analysis included both in the design process and in the construction phase. In buildings where roof edges, eaves or other construction details do not provide protection from wind-driven rain (WDR), the moisture load of the external envelope is noticeably higher, and the dominating maximum is achieved during the last quarter of the year. According to Choi (1999) and Blocken and Carmeliet (2006), the highest loads are at the top corners of the vertical wall. Abuku et al. (2009) studied the impact of WDR and concluded that WDR loads can have a significant impact on mould growth, especially at the edges of the wall. Therefore, it is essential to consider moisture loads in that particular area of the vertical surface when designing buildings without roof eaves in order to ensure a satisfactory hygrothermal performance of the external envelope.

Analysis showed that the orientation of the building has its role in the structure's MC and consequently in its dry-out capability. In Estonian climate with south and west winds prevailing, the moisture load is correspondingly higher in structures opened to the south, south-west and west directions (Jaagus and Kull 2011). Initial moisture redistribution analysis in areas with higher moisture loads showed that inner zones may contain higher volumes of moisture and the dry-out capabilities are weaker in depth of a massive structure compared to areas closer to the external surface.

To follow the up-to-date energy efficiency and nZEB requirements, calculations of moisture dry-out capabilities must be made, and proper solutions designed as the calculations in this study showed that the IMC in the exterior concrete slab might be high, about 110 kg/m^3. After the installation of an additional insulation onto the exterior side of the original wall, the moisture will dry out, the temperature of the outer layers of that wall will drop and its estimated *RH* level will stay most likely at 50–60% as maximum. This means that at least 40–50 kg/m^3 of water needs to dry out from the original wall.

5.3 Performance of the PCLP wall after the renovation with prefabricated timber frame insulation elements

Considering the fact that it is common in cold climates that most of the year the indoor moisture load is higher than on the outside, the hygrothermal design of building envelopes should consider the moisture flow that may penetrate into the building envelope directed from inside to outside and pass layers with different properties in the building structures (e.g. cracks or open junctions in the internal side of the structures). In the course of this process, unaccounted moisture may accumulate in the structure's layers and increase the moisture load and cause mould formation in addition to higher thermal transmittance (Vinha et al. 2013). In the course of the current study, analysis of the calculation results confirmed that both the IMC and hygrothermal properties of the air and vapour barrier materials are decisive for hygrothermal performance, particularly for the risk of mould growth and changes in it. The values of the *RH* and mould index, and consequently the probability of mould formation, may vary to a very high extent in the case of walls with the same thermal transmittance when there are differences in the initial moisture load as well as in air, vapour and wind barrier materials.

The calculations with PE-foil with high vapour resistance used as an air and vapour barrier between the original wall and the installed insulation element (see Figure 4.11 and Figure 4.12) showed that there is a very high risk of humidity problems. Moisture, drying out and moving through the existing wall layers, is trapped behind the foil (see points t4&RH4 and t5&RH5 in Figure 4.17) and the *RH* level will stay there in the full saturation state for many years. Mould index calculation results in critical point 4 (see t4&RH4 in Figure 4.17) with PE-foil as the air and vapour barrier layer agreed with the results of *RH* levels and confirmed that a high IMC of the original concrete wall (in this case $w > 55$ kg/m^3) will lead to extensive moisture accumulation. When using a vapour barrier with varying vapour resistance (e.g. $0.2 \text{ m} \leq S_d \leq 5 \text{ m}$), the risk of moisture accumulation between the prefabricated element and original wall is lower and the equilibrium state in the prefabricated element may be reached in 4–6 months. The study by Coupillie et al. (2017) concluded that the application of a vapour retarder between the new element and the existing construction and the protection of the existing inner part are advantageous. However, it is very important to note that this approach is true if outer layers (i.e. insulation and wind barrier) do not resist the moisture flow compared to the inner layer beneath and the vapour control layer ensures the required moisture resistance. Many authors (Fedorik and Illikainen 2013, Vinha et al. 2013, Gullbrekken et al. 2015) have pointed out that in highly insulated buildings, high thermal resistance and water vapour permeability of the wind barrier layer are the key components of the well-functioning highly insulated building envelope.

Still, sometimes there is an unavoidable need to consider alternatives. If the design or transportation restrictions of factory-made insulation elements do not allow the use of thin rolled vapour retarders or if a rigid and stiffening layer on modules is required, then OSB or some similar board will be a functional solution. However, the calculations in this study demonstrated that such solution has strict limits: during the construction works when prefabricated elements are installed onto the building, the IMC of the original wall construction must not exceed the limit w = 75 kg/m^3. According to the measurements and calculations (Ilomets and Kalamees 2013), the moisture content is about 75 kg/m^3 in original, previously constructed and in good condition concrete elements only in the dry summer period. Therefore, such IMC is difficult to achieve as in the Estonian humid and cold climate conditions, starting from September and lasting until the end of April, the average MC in concrete elements is around 80–90 kg/m^3, after a heavy rain it may increase even up to 137 kg/m^3.

As calculations in the thesis show, there will be big differences in the hygrothermal performance and risks of failure if the designed air and vapour barrier and/or wind barrier layers are changed in the construction process without complementary control calculations. A longer constructional moisture dry-out period will worsen the hygrothermal condition of the entire building and its envelope. On the other hand, if a vapour control layer is missing, the mould risk at the conjunction surfaces of original and new layers will be low, but the further moisture flow cannot be controlled. It is very important to take into account the possible building ageing, technology mistakes as well as cracks and open joints in original structures that allow uncontrolled moisture flow to move towards outer layers where it will cause problems due to moisture excess as described above. Because of the unknown state of original structures, primarily their IMC, it is a firm suggestion that hygrothermal measurements of the existing structures be conducted before final design decisions and construction works.

The evaluation of the building's condition, presence and properties of the air and vapour barrier layer controlling the penetration of moisture, as well as a high quality of installation, are very important in case of the highly insulated envelopes and in the renovation process towards nZEB. We fully agree with Ryńska et al. (2019), who studied and stressed the importance of decisions made in the design and construction processes: decisions must be made with the awareness that a minor change in one discipline may cause a major change in other ones. We see that the building envelope of the future nZEB needs careful integrated design and that material replacement during the construction works without re-calculations of the designed solution should not be allowed.

5.4 Commissioning of moisture safety

The measured and calculated values of temperatures and *RH* in the analysed points of the PCLP wall insulated with prefabricated elements correspond well to our expectations, listed in publications II and III. Moreover, they are in agreement with the boundaries defined during the preliminary analysis and the design phase of moisture safety and performance quality commissioning process.

Nevertheless, the calculations in this study show that after rain, the MC in the exterior concrete slab of a PCLP (see Figure 4.7 to Figure 4.9) may exceed the critical limit (i.e. $w > 110$ kg/m^3). Still, the risk is very low most time of the year. Only the late autumn and winter months (November, December and January) are the season of high-level risk. In summertime the probable maximum MC level may reach $w \approx 85$ kg/m^3 and in early spring or autumn $w \approx 95$ kg/m^3. These MC levels are below the critical and do not pose a high risk of degradation or moisture damage if elementary requirements of moisture safety and working instructions and methods are followed. If the MC of the wall has surpassed the critical level, a way out is to stop the installation for some days to let the wall dry out (see Figure 4.9 and Figure 4.10). However, for a contracting company stopping the installation and waiting for a week or even longer for the MC of the original wall to be back under the critical level may be out of the question. Another option is to protect the wall exterior surfaces in advance with foils or tarpaulins if the weather forecast shows heavy precipitation in the next days. Hradil et al. (2014) studied the influence of WDR overflow during building and noticed similarly to our conclusions that the penetration of rainwater during the construction or during the use of the building is harmful to structures. Therefore, difficult decisions have to be made between the contractor, constructor and moisture safety expert to find a balanced way between moisture safety and contracting deadlines.

The measurements of the *RH* and MC (*w*) of the structures and calculations of the mould index (*M*) of the pilot building confirmed that critical moisture levels were not exceeded. In addition, these studies showed that a well prepared hygrothermal analysis and the implementation of design solutions during the installation process serve as prerequisites for a successful outcome. We agree with other authors (Vinha 2007, Geving 2017, Colinart et al. 2019) that it is highly important to consider the weather conditions and that on-site moisture safety rules must be strictly followed to reach good results. A study in Finland (Winter et al. 2012) proved the importance of moisture safety measures and of controlling the production conditions of timber prefabricated systems and stressed the advantages of these measures to achieve a high-quality final result. If critical levels are surpassed, moisture problems will occur, weakening the properties of materials. A rise of the volume of spores and bacteria of fungi in the indoor air and on the surfaces will be harmful to human health as well. Furthermore, a high MC induces mould formation and degradation of structures, which may lead to a very complicated and expensive reconstruction of the whole building envelope. Problems of moisture safety are also well studied in other countries and the same critical points are stressed (Fedorik et al. 2015, Gullbrekken et al. 2015).

It is also evident that a design that does not consider a number of important physical phenomena, including the variation of material properties, dynamics in MC and weather dissimilarities, underestimates the real state of the building. By using the analysis of the PCLP wall in the pilot project as an example, it was confirmed that a short-term superficial observation of the MC on the surface area of the material does not reflect the precise amount of moisture in the structure studied. Due to the redistribution of moisture, at a depth of 50 mm the MC may reach a level twice as high as at the surface and its dry-out period may be almost a year to reach the MC of the surface (see Figure 4.33). Therefore, the use of a proper weather protection kit with proper moisture-proof sealants, both for delivered materials and structures, should be mandatory. Use of water repellent, which minimises moisture adsorption and allows excess moisture dry-out, could be another option (especially for high buildings). Also, the monitoring of weather forecasts (for possible precipitation) at the work site is a good way to avoid mistakes such as those described in this study.

Our study showed that the common knowledge of the civil engineer might be insufficient to solve more complicated tasks of building physics. To guarantee a good moisture safety management in the design and construction process, involvement of a responsible specialist on moisture safety would be necessary. For larger countries, special occupational qualification standards are appropriate. For smaller countries, where more universal engineers are required, the demand can be solved by continuing education. The Building Code (RT I, 21.12.2019) requires moisture safety (a constructed building may not present a threat to health). Also, more detailed guidelines are needed for the implementation of these requirements. The Swedish moisture safety standard (ByggaF 2013) is a good example of this scenario.

Despite some setbacks due to the contractor's insufficient competence at the beginning of the pilot project, good results in moisture protection were attained with the help of co-operation between the developer, contractor and experts. It was proved that the monitoring of moisture safety and quality commissioning are unavoidable steps in deep energy and nZEB renovations. In Finland, well arranged commissioning of moisture safety and buildings at a larger scale (Hienonen et al. 2017) has been implemented successfully and we can take this as a good example to introduce an analogous system.
Although the existing methods of commissioning (SQUARE 2008, ByggaF 2013, Kosteudenhallinta.fi 2019) are very good, some updates that take local practice into account may be necessary. We see that several developing steps should be taken by authorities locally, both in legislation and standardisation practices, to keep up with the changing demands and behaviour of tenants and owners of nZEB. It is also necessary to force contractors and developers to put quality assurance and moisture safety commissioning processes into practice as a mandatory part of contracting. This has been pointed out by other authors as well (Mjörnell et al. 2012, Jankovic 2019) and may serve as a useful tool against major faults and possible damage claims.

One of our suggestions, based on lessons learnt during the current research, is that a certification system should be introduced for building physics specialists – professional moisture safety experts – who will manage the moisture safety programme and guarantee that it is strictly followed in highly insulated buildings industry and nZEB contracting.

5.5 Material combinations and energy and cost calculations of prefabricated timber frame insulation elements for deep energy renovation

The research task of this phase of the study was to find among results obtained combinations that are most consistent with requirements of the nZEB renovation (new buildings and major renovation), considering possible hygrothermal risks and costs. Earlier studies (Vinha 2007, Geving 2017, Colinart et al. 2019) confirm that for deep renovation of existing external envelopes the most proper solutions are with insulation layers with low water vapour resistance (both for main insulation and wind barrier layers) and vapour barriers/retarders with varying vapour resistance capability. Solutions where the vapour resistance of the outer layer is higher and with a lower thermal resistance (e.g. sheathing membrane, strand board or gypsum board) compared to MW or CW may cause excess humidity accumulation, which in turn might cause a higher mould growth risk with envelope degradation. It was concluded hereinbefore that in addition to energy performance it is necessary to pay special attention to moisture safety measures in the design and building processes of highly insulated buildings.

High thermal resistance and water vapour permeability of the wind barrier are key components of a well-functioning building envelope. This is validated by the results of calculations of mould index indicating a rise of mould growth risk with increasing vapour resistance of the outer layer of elements (e.g. sheathing membrane vs. MW board) and with greater insulation thickness (i.e. with the decrease of temperature and the corresponding increase of *RH* in external layers of the structure). Nevertheless, cement fibreboard gave better results in some cases compared to wood fibreboard wind barrier (although it has lower water vapour permeability and thermal resistance) because of its larger mould tolerant surface. Comparison of the use of MW and CW showed that owing to the relatively high moisture buffering capacity of CW, constructions insulated with it can withstand much higher moisture loads without substantial mould growth risk. It has been verified by other research as well (Kreiger and Srubar 2019). Nevertheless, in case of greater thicknesses of insulation and lower water vapour permeability of surface layers, the risk of mould growth may rise with CW insulation as well.

In the renovation of the existing buildings with prefabricated insulation elements it is very important to take into consideration that the use of a vapour barrier layer with very high vapour resistance (e.g. PE-foil) may cause accumulation of built-in moisture between the original wall and the installed vapour-tight layer of the insulation element and lead to the condensate state there for a very long time (according to our studies, even up to 4–5 years, see publication III). On the other hand, the decision to give up the use of a vapour control layer between the existing envelope and the installed element may result in moisture damage and mould growth related problems, particularly in case the moisture content of the original wall is close to saturation level (e.g. rainy periods in late summer or in autumn may cause the original wall's external layer to become very wet, up to *RH* = 100% because of wind-driven rain) and/or when the water vapour resistance of the outer layer of an element (e.g. wind barrier) is too high to let the built-in moisture dry out as fast as necessary for satisfactory hygrothermal performance of the whole system (Mundt-Petersen 2015). This can be seen in Table 4.2 and Table 4.3, where combinations without a vapour barrier layer show a higher mould growth risk compared to solutions with a vapour barrier layer, particularly in the area behind the wind barrier layer. The reason here is the higher *RH* in critical points due to the moisture flux, which is more intensive in the structure without a vapour control layer between the original (and usually with a high content of built-in moisture) wall and the installed insulation elements.

It is very important to point out that the differences in calculated mould indexes presented are caused also by the different mould growth sensitivity classes applied for materials; besides, the considered critical points were different when solutions with and without air and vapour barrier layers were compared. With air and vapour barriers B1 and B3 the highest moisture load is in points P4 and P5 (between the vapour barrier and original wall) but without vapour barrier (alternative B2) the highest loads are in points P6 and P7 (between the wind barrier and element's insulation layer) (see Figure 3.16 for analysed points and publication VI, Table 1 for description of material layers).

Results in Table 4.2 and Table 4.3 demonstrate the importance of the consideration of materials when designing the additional insulation onto the original envelope. Restrictions of some choices are clearly seen (e.g. PE-foil as a vapour barrier between the original surface and the insulation element should not be used in any of the proposed solutions). Any careless changes in the designed materials (or their properties) may lead to unsatisfactory consequences. Not only the selection of materials but also the critical point (where the risk of mould formation is the highest in this combination) has to be strictly examined and results followed to build moisture safe highly insulated envelopes.

Therefore, if there are technological obstacles or other justified reasons for not to use a vapour barrier (control) layer between the original wall and the prefabricated timber frame insulation elements, it is crucial to reconsider the mould growth sensitivity class of wood or wood-/cellulose-based products with a high content of nutrients favourable for fungal growth. Because of the higher moisture flow in the absence of a vapour control layer in the direction from the original wall towards the prefabricated timber frame element, in case of the use of untreated wood (e.g. not planed, pine or spruce sapwood) the mould growth sensitivity class 'very sensitive' should be assigned to the surfaces of timber details. In a cold and humid climate this will lead to mould index $M \geq 2$, i.e. mould formation risks are considerably high. A strict recommendation is that a vapour control layer with varying vapour permeability (e.g. 0.2 m at *RH* 85% $\leq S_d \leq$ 5m at *RH* 20%) should be used while the use of vapour barrier products with high vapour resistance (e.g. PE-foil, $S_d \geq 50$ m) should be avoided to keep the moisture flow controlled when additional insulation elements are installed on top of the existing moist external envelope. It is in a good agreement with and was well studied and described in our past research as well (see publication II and publication III).

Our results showed that if mould growth is avoidable, then MW wind barrier board, wood fibreboard and cement fibreboard are the preferred materials. From the production perspective, a rigid wind barrier (wood fibreboard and cement fibreboard) is preferable due to easier and quicker installation procedures. Nevertheless, these wind barriers might not be suitable if the moisture content of the original facade is high. Construction practice has shown that it is impossible to wait for better weather and to dry out the facade. Therefore, the insulation element should include a safety factor, and MW wind barrier board is the best solution because of its high water vapour permeability and thermal resistance.

Blowing in loose-fill insulation is a typical method of CW insulation. To prevent the settling of the insulation layer of CW, the density of loose-fill insulation in walls should be much higher than commonly assumed for attics. Rasmussen (Rasmussen 2005) argued that to prevent settling the density of loose-fill CW insulation in the wall should be

$\rho \geq 65$ kg/m³ to compensate for any humidity cycling and creep. However, he did not consider the vibration due to transportation (which is unavoidable for prefabricated insulation elements). Therefore, the density of loose-fill insulation for prefabricated insulation elements should be much higher than for attics. Higher density requires more material, resulting in higher cost and heavier elements.

Building contractors and producers of prefabricated insulation elements have given critical feedback about the design and installation of insulation elements. The most objective and practical ones stress the indispensable need of a pre-installation phase of work: well-prepared measurements of the existing situation should be carried out and the results translated into detailed and precise design documentation. Clients and moisture safety experts have pointed out the importance of proper handling of materials during transport to the building site and especially during the on-going works under the changing and wet weather conditions. The use of protective sealed foils and well-planned precautionary activities in case of precipitation are a must to avoid later problems with moisture damage, degradation of structures and unsatisfactory indoor climate.

Facade cladding choices (e.g. wooden or plastic boarding/siding, metal profile sheets, cement fibreboards, facade stone cladding etc.) are rather made by personal preferences of each customer. The preferred materials are dissimilar in unit price as well as mounting and maintenance costs. However, these costs may account for a large proportion of the total renovation budget. Therefore, circular use of materials could be one way of reducing the cost of facade cladding.

In comparison of the energy performance on base of variation of total delivered energy we can see that differences were relatively small because the energy for space heating was one of the smallest components of total energy use. But it is important to see that indoor temperature heating set point was 21 °C. It was shown by preceding studies (Branco et al. 2004, Hamburg and Kalamees 2018, Hamburg et al. 2020) that indoor temperature set point used is higher, typically 22 °C for post-renovation situation. That 1 °C rise will affect the amount of delivered energy for space heating in average +33%, EPV value for +1.2…+1.4% and the global cost for +1.0…+1.3%.

Compared to conventional solutions of energy refurbishment (e.g. ETICS or analogues), the cost level of the analysed prefabricated elements for the end-user is still slightly higher (about 101–164 €/m^2). The current market prices of the ETICS with expanded polystyrene (EPS) insulation are around 90–100 €/m^2 and with rendered MW around 100–120 €/m^2. This cost difference together with some shortage of expertise of participants is described also by other researchers as the main reason why prefabricated insulation elements are not yet in a competitive market position (Lattke et al. 2009, Mjörnell 2016). Renovation activity must be increased to a very large extent to fulfil EU decarbonisation targets. Estonian practice has shown (Kuusk et al. 2019) that increased renovation volumes create new problems such as shortage of contactors, construction workers and construction materials, which results in increased renovation costs. The ETICS and other rendering methods have been on the market already for many decades without moving forward towards industrialised production. The main way to increase the efficiency and reduce the cost is to raise the automation level and to find means of unification of products for faster design, mass production and installation. Other industries have shown that industrialisation and mass production decrease the costs. Therefore, the prefabricated elements will obviously have cost advantages in the future.

6 Conclusions

6.1 Parameters influencing the hygrothermal performance of the highly insulated timber frame structure

Highly insulated timber frame structures with thermal transmittances $U \leq 0.17$ W/(m^2·K) and with several material combinations were analysed by hygrothermal simulations to examine the influence of the moisture content and the increase of the thermal insulation thickness on the hygrothermal performance of the building envelope. The risk of mould growth was used as the performance criterion to predict the acceptability of the hygrothermal performance.

Hygrothermal analysis indicated that it is possible to keep the mould index level $M < 1$ with all studied insulation materials and wind barriers and thus, help to ensure moisture safety of highly insulated building envelopes. It is very important to design properly the combination of thermal and vapour resistance of the wind barrier, vapour and air resistance of the vapour barrier as well as the moisture capacity of insulation and wind barrier layers to limit the excessive humidity caused by moisture in the structure.

Due to the higher relative humidity (*RH*), a higher risk of mould growth was found between the insulation and the wind barrier in structures with lower thermal transmittance when the thickness of the insulation was the sole modified parameter. With wind barriers that have a higher thermal resistance and water vapour permeability, the increase of the mould growth risk in the course of the reduction of the thermal transmittance of the building envelope was lower. When the wind barrier has low thermal resistance and vapour permeability, it may need additional thermal insulation on the exterior side to minimise mould formation risks in the contact surface of the wind barrier and the insulation layer. The drying out time of constructional moisture was longer for walls with lower thermal transmittance, causing also a higher risk of mould growth.

The results of comparison of the insulation materials revealed that the structure had a lower mould formation risk with cellulose insulation than with mineral wool if the other materials remained unchanged. In conclusion, the highly insulated building envelope meeting requirements of nearly zero energy buildings (nZEB) needs very careful hygrothermal design and thorough consideration of material properties. Interaction has a decisive role in the process of design and construction works at the building site. Engineers and designers should include hygrothermal modelling into design practice to ensure the moisture safety of structures and sustainability of nZEB in the long term.

6.2 Moisture content and dry-out capability of the PCLP wall

The design of highly insulated external envelopes is a demanding process where hygrothermal analysis has a very important role. Based on studies performed, we may claim that prior to the installation of new layers onto an existing envelope, which may probably change the hygrothermal performance considerably, the designer has to examine the existing structures thoroughly and take into account not only the indoor and outdoor climate but also the consequences of constructional moisture loads, dry-out capability and orientation of the designed structures.

The analysis of the moisture dry-out potential is based on the cold climate in Estonia and it could be an exhaustive material for further hygrothermal design of additional insulation of buildings constructed using prefabricated concrete large panel (PCLP) elements. The calculations in this research showed that the initial moisture content (IMC) in the concrete slab with the impact of wind-driven rain (WDR) and other weather conditions, orientation and seasonal factors is 137 kg/m^3 as maximum, 110 kg/m^3 as 90% level and 90 kg/m^3 on average. In Estonia, the moisture load to wall surfaces is highest in the south-west direction, through October to December and in January. The moisture dry-out from the concrete envelope was 23 kg/m^3 within the first 6 months after the installation of the elements and thereafter, during the next 12 months, 12 kg/m^3. The equilibrium state of the PCLP wall was reached after 24 months from the start of the installation of prefabricated elements onto the original PCLP wall.

6.3 Commissioning of moisture safety

Within this research, quality commissioning of moisture safety of nZEB renovation of a PCLP building with prefabricated timber frame insulation elements was performed. We claim that, with preliminary analysis and continual surveillance, it is possible to attain good results and use effectively prefabricated timber frame elements in deep energy and nZEB renovation. According to measurements and calculations, the settled level of mould index (M < 1) and critical moisture content of the PCLP wall (w = 110 kg/m^3) were never exceeded in the critical points.

In the design and construction of the highly insulated envelopes several basic principles must be followed. The most important ones for achieving moisture safety and the targets of indoor climate and energy consumption are clarification of the aims and needs, compliance with the design regulations and monitoring of the processes in all stages of the project. Above all, strict rules, a follow-up of moisture safety at the work site and highly motivated and skilled employees with effective management are of the utmost importance.

There is a significant need for the implementation of a local professional certification system for moisture safety specialists. Moreover, the results of the current research provide reasons and inspiration to institutions, real estate developers, engineers and designers to extend their design practices and improve quality assurance processes and standardisation.

6.4 Conclusions of post-renovation analysis of the prefabricated timber frame insulation elements for deep energy renovation

The hygrothermal performance of the external walls constructed of PCLP and insulated additionally with prefabricated timber frame insulation elements in Estonia was analysed in this research to collect data for further development and hygrothermal design of nZEB renovation of PCLP buildings. The application of prefabricated timber frame insulation elements in the process of deep energy renovation of a PCLP apartment building was motivated by many goals:

- To demonstrate this innovative way of renovation of apartment buildings aimed at improving energy efficiency, hygrothermal performance and aesthetics of buildings and technology of prefabricated renovation elements, including the integration of multifunctional components, e.g. climate control by ventilation ducts embedded into the elements;

- To give an opportunity to local designers and producers of timber elements to participate in product development and innovation with a solid scientific support from university;
- To achieve high-quality results with shortened as much as possible time spent on manual fieldwork by using prefabrication of installation-ready units in controlled premises of a factory under production and materials quality control;
- To test the renovation method that is intended to be realisable in all seasons of the year and with as little as possible disturbance of habitants or owners of the buildings. The idea is that proprietors can stay in their premises and continue normal life during the ongoing installation works outside the building.

Meeting the requirements of the hygrothermal performance of the studied solutions in a cold climate was achieved by using a vapour barrier with varying vapour resistance (0.2 m ≤ S_d ≤ 5 m) when the IMC of the original PCLP wall $w \leq 110$ kg/m^3 or with 22 mm OSB as the vapour control layer when the IMC of the original PCLP wall $w \leq 75$ kg/m^3 or with PE-foil as the air and vapour barrier when the IMC of the original PCLP wall $w \leq 55$ kg/m^3.

A functional assembly solution is presented as a final design of the pilot building (see Figure 4.17 and Figure 4.18). This is a modified alternative of the initially designed solution (see Figure 3.11) with the consideration of important details and units from the point of view of hygrothermal performance.

The most important factors affecting moisture dry-out are similar to those causing risks related to the formation of mould and water vapour condensate. Contrary to the common timber-frame wall in which the PE-foil as the air and vapour barrier does not cause any serious problems to the hygrothermal performance, in additional insulation elements it prevents the constructional moisture dry-out and causes a high risk of mould formation. In other words: an air and vapour barrier layer with high water vapour resistance on the surface of the moisture-containing structure may lead to high moisture accumulation between the installed air and vapour barrier and the original wall structures. The dry-out of initially moist concrete slabs that have been insulated and covered with an air and vapour barrier layer may take several years. The condition of original structures and uncontrolled high indoor moisture excess load may cause unexpected moisture flow and increase humidity loads in the structure.

After the load-bearing requirements are fulfilled, other layers in the building envelope are frequently designed according to the required thermal transmittance and visual appearance. However, as the present and previous studies show, the design of the hygrothermal performance of the future nZEB and highly insulated building envelope based on the common knowledge and practices may most likely appear insufficient. Moreover, also the expected climate change forces us to reassess the common practices.

Nevertheless, it is possible to achieve good results and build sustainable solutions according to the up-to-date requirements of nZEB with prefabricated timber frame insulation elements used for renovating of PCLP buildings in cold and humid climate. The prerequisites for good hygrothermal performance and design include preliminary measurements of the building's state, carefully considered vapour control and installation of an airtight layer on the concrete envelope with its water vapour permeability controlled with hygrothermal calculations and insulation and wind barrier layers with high thermal resistance and vapour permeability.

6.5 Material combinations and energy and cost calculations of prefabricated timber frame insulation elements for deep energy renovation

A complex method of selection and analysis to find the most appropriate set of prefabricated insulation elements for major renovation of apartment buildings was introduced in this research. The most consistent sets, based on hygrothermal performance, handling and production characteristics and reasonable cost, were presented.

Mineral wool board with special wind barrier facing is the best material for wind barrier from the perspective of hygrothermal performance. In cold and humid climates PE-foil cannot be used as an air and vapour barrier layer in prefabricated insulation elements as it does not allow constructional moisture to dry out and causes condensation and mould growth. Compared to mineral wool, cellulose insulation has advantages concerning hygrothermal performance, but its installation density should be high ($\rho \geq 65$ kg/m^3) to avoid settling due to humidity cycling, creep and vibration on the transportation way from production facilities to the building site.

The variation of thermal transmittance of a well-insulated external wall has minor influence on the energy performance of the building. It is possible to renovate an apartment building to correspond to the new building nZEB level with efficient district heating and to fulfil the nZEB requirements for renovation in case if common district heating is used.

Cost analyses showed that materials affecting moisture safety and energy performance do not influence the total cost too much. Therefore, it is possible to select the best materials from the perspective of hygrothermal and energy performance without increasing the renovation price noticeably. The facade cladding had the highest influence on the initial cost of the insulation element (±13–15%). This means that the materials having the greatest effect on the hygrothermal performance of the building envelope have smaller influence on the initial cost. It is possible to guarantee moisture safety without paying a high relative difference cost. Decreasing the global cost of elements would increase the mould growth risk.

7 Future research

It is essential to continue to study the perspectives of prefabricated timber frame insulation elements and their hygrothermal performance on other types of structures as well. There are large numbers of apartment and office buildings with poor thermal efficiency and unsatisfactory indoor climate, constructed decades ago, built from aerated autoclaved concrete, bricks or natural stones. The use of prefabricated timber frame insulation elements for their improvement might be a good option to fulfil the nZEB requirements in the large-scale renovation of the buildings coupled with insignificant disturbance to proprietors of the buildings.

It is recommended that in the future research of prefabrication of insulation elements some relevant aspects be addressed concentrating on the following:

- Research and design of elements for zero- and plus-energy buildings with integrated appliances (e.g. green facades, photovoltaic, solar and other energy producing or climate systems);
- Detailed studies of structural units and connections of elements to guarantee weatherproof joints, airtightness of the envelope and energy efficiency of the solution;
- ‘Simpler is smarter’ solutions (e.g. clever intersections, joints, hanging systems, smart connectors, mounting technology etc.);
- Suitability for different types and sizes of buildings;
- Automation of the design and production;
- Implementation of typified structural solutions, eligible for mass production;
- The range of questions with cost-efficiency in all phases (incl. design of attractive grant schemes for end-users);
- Life-cycle assessment, recycling of materials and circular use in the process of renovation and in the lifespan of buildings with prefabricated elements.

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The effect of thermal transmittance of building envelope and material selection of wind barrier on moisture safety of timber frame exterior wall

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ABSTRACT

The nearly zero energy buildings (nZEB) ideology of the future obliges, first and foremost, that heat losses should be reduced remarkably compared to the present levels. The current study examines the potential hygrothermal risks and their effect on highly insulated timber frame exterior walls under cold climate conditions. The focus is on the timber frame exterior walls with thermal transmittances between 0.17 and 0.08 W/(m^2 K), with different material combinations and boundary conditions, where the risk of mould growth as a performance criterion was used. A careful selection of materials allows to design moisture safe timber frame exterior walls and provide low thermal transmittance. It was found that the relative humidity and the risk of mould growth are higher and the drying out period is longer in walls with lower thermal transmittance when insulation thickness is the only changed parameter. Wind barriers with higher thermal resistance and water vapour permeability indicated a lower increase of mould growth risk in structure in the course of reduction of the thermal transmittance. Therefore, the building envelope of the future nZEB needs a careful hygrothermal design.

1. Introduction

Minimising heat loss through the building envelope is one of the key factors to ensure a very high energy performance like in nearly Zero Energy Buildings (nZEB) [1], passive houses or other national low-energy building standards. Heat loss through the building envelope depends on the thermal transmittance U (W/(m^2 K)) of plane structures (walls, roof, windows etc.) as well as on linear and point thermal transmittance of connections of structures, disconnections of insulation (i.e. thermal bridges) and air leakages of the building envelope. All of these components that have a negative influence should be minimised when the target is low heat loss through the building envelope.

Several tasks that are related to the hygrothermal performance of structures need to be solved in the design and construction process of building envelopes with thicker thermal insulation and lower thermal transmittance to guarantee the moisture safety of the building envelope. Thicker insulation (i.e. bigger volume of material in building envelope) may contain more built-in moisture, which has to dry out after the construction process. A smaller heat flow slows down the dry-out rate of moisture and it could be another factor, which influences how a highly insulated wall becomes more sensitive to moisture damages. Although the critical moisture level for mould growth increases with temperature decrease [2,3], the presence of sufficient relative humidity (RH) is the most critical factor influencing mould growth.

Kurnitski [4] and Airaksinen [5] showed higher humid conditions in highly insulated outdoor ventilated crawl spaces in Finland. Thicker thermal insulation between the living space and attic and a lack of a warm chimney have increased moisture and mould damages in Sweden [6]. In addition, houses frequently renovated with additional attic insulation have led to low temperatures in attic space and hence a higher humidity [7] in Sweden. Vinha et al. [8] showed that stricter requirements in Finland for the energy efficiency and increased thickness of thermal insulation will lead both to changes in building technology and in structures and may become a source of substantial moisture-related problems in building envelopes in the far future as a result of the climate change. Langmans et al. [9] analysed four highly insulated timber frame walls with an exterior air barrier in laboratory conditions and showed an increased moisture flow at the upper part of the walls driven by buoyancy forces. Kalamees et al. [10] have pointed out that the performance of the building service systems and moisture safety should be carefully focused on already in the preliminary stages of design while planning buildings with high energy efficiency.

Based on preceding studies, we may declare that in order to design building envelopes with a thicker thermal insulation layer and lower thermal transmittance, the designer has to solve many tasks related to the hygrothermal performance of a building

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envelope. However, after fulfilling the load-bearing requirements, other layers in the building envelope are usually designed according to the required thermal transmittance and visual appearance. But the design of hygrothermal performance of the future nZEB highly insulated building envelope, based the current knowledge and practices, or on the Glaser method [11], may most likely appear insufficient.

This study examines the potential hygrothermal risks and their impact on a highly insulated timber frame exterior wall under cold climate conditions in Estonia. The questions that are addressed in the current research are the following:

1) What is the extent and direction of the influence of increase of thermal insulation on the hygrothermal performance and moisture safety of the timber frame exterior wall?
2) What kind of material properties should be preferred to avoid favourable conditions for mould growth and humidity accumulation?

These aspects were studied by parametric simulations, carried out for a timber frame exterior wall that corresponds to the current energy performance requirements in Estonia [12]. Various types of material properties (e.g. water vapour permeability, thermal conductivity, moisture storage) and boundary conditions were studied. The risk of mould growth was used as a performance criterion to predict the acceptability of hygrothermal performance.

2. Methods

2.1. Hygrothermal simulations and material data

The dynamic hygrothermal simulation programme Delphin, developed at the Technical University of Dresden and successfully validated [13,14], was used in this study. Delphin is a simulation programme for coupled heat, moisture and matter transport in porous building materials and it is used for different applications, e.g. calculation of mould growth risks with consideration of climate impacts, structure conditions and materials modelling.

The moisture mass balance can be expressed as:

$$\frac{\partial}{\partial t}\rho_{REV}^{m_{w+v}} = \frac{\partial}{\partial x}\left[j_{conv}^{m_w} + j_{conv}^{m_v} + j_{diff}^{m_v}\right] + \sigma_{REV}^{m_{w+v}} \tag{1}$$

where $\rho_{REV}^{m_{w+v}}$ is moisture (water+vapour+ice) density in reference to volume kg/m^3; $\sigma_{REV}^{m_{w+v}}$ is moisture source/sinks in reference to volume kg/m^{3}s; j is flux kg/m^{2}s; conv is convective; diff is diffusive; v is vapour; w is water. The energy balance is expressed by:

$$\frac{\partial}{\partial t}\rho_{REV}^{U} = \frac{\partial}{\partial x}\left[j_{diff}^{Q} + u_l j_{conv}^{m_l} + u_g j_{conv}^{m_g} + h_v j_{diff}^{m_v} + h_{voc,g} j_{diff}^{m_{voc,g}}\right] + \sigma_{REV}^{U} \tag{2}$$

where ρ_{REV}^{U} is the internal energy density in reference volume J/m^3, σ_{REV}^{U} is energy source/sinks in reference volume W/m^3, j_{diff}^{Q} is heat conduction W/m^2, j is flux kg/m^{2}s, conv is convective, diff is diffusive, g is gas, l is liquid, u is specific internal energy J/kg, h_v is the specific enthalpy of water vapour J/kg.

The calculations with this programme were made at the point of structure that was most critical with regard to hygrothermal risks, i.e. A1 (Fig. 1). The properties of materials of studied structures (Table 2) are based on the material database of programme Delphin and on the results of laboratory measurements, performed by scientists at Tampere University of Technology [15].

2.2. Simulation of mould growth

In this research we utilised a mathematical model for the calculation of mould growth, decrease and the mould index in changing conditions, designed in Finland [16,17]. According to this model, within fluctuating humidity conditions, the total exposure time for response of growth of mould fungi is affected by the time periods of high and low humidity conditions, as well as the humidity and temperature level. In the simulation of mould growth, it is crucial to know the lowest (threshold) conditions where fungal growth is possible on different materials. The boundary curve for the risk of mould growth in the range of temperature between 5 and 40 °C on a wooden material can be described by a polynomial function:

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

where t is temperature on the investigated material surface (°C) and RH_{min} represents the minimum level of relative humidity, where mould growth is possible (varies according to the sensitivity of the material) [17].

Furthermore, the importance of duration of these conditions is also significant. There are certain minimum and maximum levels for the moisture content of material, water activity or temperature, between which fungi can grow in wood. Under these favourable conditions, mould growth may start and continue at different rates. The time period, needed for the onset of mould growth and growth intensity, is mainly dependent on water activity, temperature, exposure time and surface quality of the substrate [16,17].

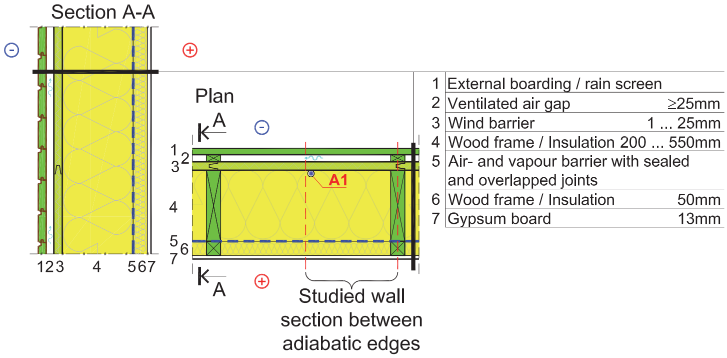

Fig. 1. Studied timber frame exterior wall.

Table 1
Description of mould indexes [17].

Mould index (*M*)	Description of mould growth
0	No growth
1	Small amounts of mould on surface (microscope), initial stages of local growth
2	Several local mould growth colonies on surface (microscope)
3	Visual findings of mould on surface, < 10% coverage, or < 50% coverage of mould (microscope)
4	Visual findings of mould on surface, 10–50% coverage, or > 50% coverage of mould (microscope)
5	Plenty of growth on surface, > 50% coverage (visual)
6	Heavy and tight growth, coverage about 100%

The critical value of the mould index (M) was set in the current research to level $M=1$ (no growth, pores are not activated) according to the mould index model to avoid the formation of mould in a structure (Table 1).

2.3. Boundary conditions

In the assessment of hygrothermal risks, the hourly data of the moisture reference year, critical to mould growth in Estonia, was used for outdoor climate [18]. Indoor climate measurements from Estonian dwellings [19–21] were used for the determination of critical indoor hygrothermal conditions. For simulations, the following conditions were used: average indoor temperature, dependent on the outdoor temperature (Fig. 2 left) and indoor humidity of class 3 (dwellings with high humidity load) (Fig. 2 right), representing high occupancy according to national appendix of EVS-EN 15026 [22], expressed as indoor moisture excess $\Delta\nu$ (kg/m^3). Initial moisture content of the building materials, used in the calculations, was equal to their equilibrium moisture content at RH=80%, and in some calculations at RH=90% of ambient air, which is common RH of outdoor air during the autumn–winter period in cold humid climate. For calculations with wet installed cellulose insulation, RH=97% was used only for cellulose insulation, while equilibrium moisture content of all other materials in those cases remained at level RH=80% of ambient air.

2.4. Studied structures and building materials

In this study, a timber frame exterior wall (Fig. 1) with different thermal transmittances U (0.17, 0.14, 0.12, 0.10, 0.08 W/(m^2 K)) and material combinations (Table 2) was analysed. In order to compare the hygrothermal indicators and to analyse their impact, different thermal insulation materials (mineral wool and cellulose insulation, installed either as a dry or wet mix), air and vapour barrier materials (polyethylene foil, kraft paper processed with polyethylene, bitumen paper), as well as wind barrier materials (wood fibreboard, dense mineral wool board, wind barrier gypsum board, chipboard) have been used in the structures, by combining these materials with each other. A timber frame exterior wall with mould index $M=1$, fulfilling the current energy performance requirements in Estonia [12], with thermal transmittance $U=0.17$ W/(m^2 K), insulated with 200+50 mm mineral wool, covered with 22 mm wood fibreboard as a wind barrier and with an air and vapour barrier (Kraft paper type A, Table 2) was used as a reference wall.

Commonly, the RH level between the wind barrier and the insulation is hygrothermally the most critical location in timber frame exterior walls in cold climate. If, in the case of walls that are insulated with mineral wool, a rigid wind barrier layer (i.e. gypsum board, chipboard) is required with the functionality of additional stabilisation of the wooden structure, then because of its low thermal resistance, an additional thermal insulation (e.g. a higher density mineral wool) can be added to it on the external side to keep RH lower and raise the temperature behind the rigid layer. RH is influenced by many factors there, most of all by climatic conditions, material properties and initial moisture conditions. Avoiding high moisture conditions and assuring a short drying out period are important properties to improve the moisture safety of the structures.

Even though the used air barrier layer should ensure the airtightness of building envelope without any considerable convection, minimum air permeability of structures is approbated also for nZEB or passive houses. Therefore, was also studied how the increase of thermal insulation influences the moisture safety of the timber frame exterior wall with air leakage rate $q_{50}=0.6$ m^3/(h m^2). The air leakage was divided equally over the building envelope of a two storey detached house. Air pressure difference was calculated based on indoor and outdoor temperature difference at 3 m' height from natural line (close to roof/wall connection). While the air leakages are concentrating usually on the connections of building envelopes [23,24] and the moisture safety is determined by air convection in connections [25], adding the air convection on the plane structure gives larger hygrothermal load compared to sole diffusion flow and gives therefore additional safety margin. The vapour resistance of vapour barrier was increased to compensate the larger moisture flow due to convection in order to keep the wall, with thermal transmittance $U=0.17$ W/(m^2 K), under the mould growth risk level (i.e. $M<1$).

It was presumed in the present work that the wooden boarding or brick cladding for facade provides firm rain-screen for the thermal envelope. Therefore, the impact of rain as moisture transfer process has not been taken into account.

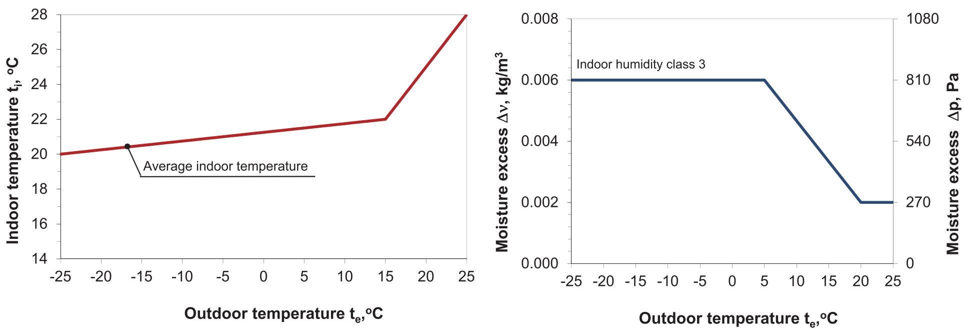

Fig. 2. Dependency of indoor temperature (left) and design value of moisture excess (right) on the outdoor temperature.

Table 2
Properties of materials used in simulations.

Material	Density ρ, kg/m^3	Thermal conductivity λ, W/(m K) RH			Water vapour permeability (*resistance), $\delta_p \cdot 10^{-12}$, kg/(m s Pa) *$Z_p \cdot 10^9$, m^2 s Pa/kg RH							Moisture storage function w, kg/m^3 RH						Water absorption coefficient A_w, kg/(m^2 s$^{0.5}$)
		33%	55%	86%	0%	33%	55%	75%	83%	97%	100%	33%	55%	75%	83%	97%	100%	
Wood (pine)	532	0.110	0.120	0.130	2.2	2.2	2.2	5.3	8.7	13.0	24,0	32.3	45.0	80.1	108	185	870	0.010
Wood fibreboard	270	0.048	0.049	0.050	43.0	43.0	43.0	43.0	43.0	43.0	43.0	12.5	20.0	28.0	40.0	75.0	140	0.0054
Chipboard (OSB)	646	0.110	0.120	0.130	0.99	0.99	0.99	0.99	0.99	0.99	0.99	31.0	46.0	78.0	110	180	839	0.011
Wind barrier gypsum board	774	0.190	0.190	0.190	25.1	25.1	25.1	25.1	25.1	25.1	25.1	6.1	8.4	9.5	11.5	23.8	500	0.076
Gypsum board	574	0.190	0.200	0.210	28.7	28.7	28.7	28.7	28.7	28.7	28.7	4.6	6.1	7.2	8.4	18.0	371	0.0761
Mineral wool wind barrier	104	0.031	0.031	0.031	110	110	110	110	110	110	110	0.4	0.5	0.7	1.7	4.7	7.0	
Mineral wool insulation	22	0.037	0.037	0.037	165	165	165	165	165	165	165	0.45	0.54	0.8	1.0	1.9	2.5	
Cellulose insulation (dry)	37	0.048	0.048	0.049	152	152	152	152	152	152	152	1.9	3.1	4.8	6.8	13.0	430	0.095
Cellulose insulation (wet)	60	0.041	0.042	0.043	115	117	129	143	148	148	148	3.1	5.0	7.8	11.0	21.0	570	0.065
Bitumen paper A	840	0.110	0.120	0.120	*0.46	*0.46	*0.46	*0.18	*0.08	*0.08	*0.08							
Bitumen paper B	940	0.110	0.120	0.120	*0.69	*0.69	*0.69	*0.32	*0.20	*0.20	*0.20							
Kraft paper A	990	0.110	0.120	0.120	*5.8	*5.8	*5.8	*2.6	*1.6	*0.9	*0.9							
Kraft paper B	756	0.110	0.120	0.120	*19.6	*19.6	*19.6	*19.6	*19.6	*19.6	*19.6							
Kraft paper C	940	0.110	0.120	0.120	*50.0	*48.0	*47.5	*47.0	*46.5	*46.0	*46.0							
PE foil 0.2 mm	980	0.400	0.400	0.400	*90.0	*90.0	*90.0	*90.0	*90.0	*90.0	*90.0							

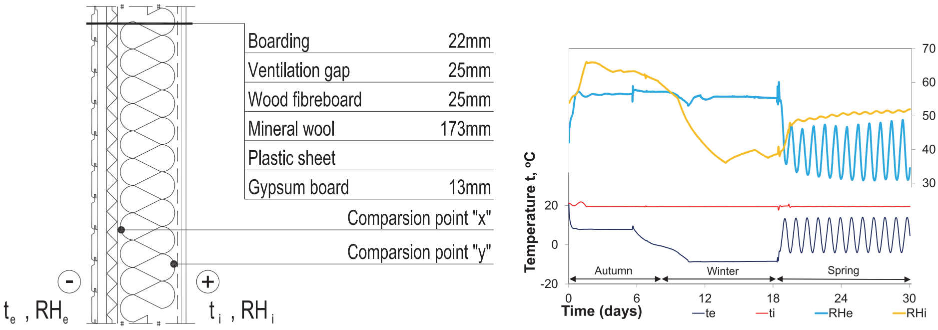

Fig. 3. Section of a structure, used for validation of simulation model (left) and measured internal (i) and external (e) temperature (t) and relative humidity (RH) (right).

2.5. Model validation

The simulation models were validated on base of several laboratory tests of timber-framed wall structures, performed at Tampere University of Technology [26]. An example of timber-framed wall structures that was used is shown on Fig. 3 left. The laboratory equipment consisted of warm chambers (to model indoor climate) and protective chamber (to model outdoor climate) that situated in a big freezer where the outdoor temperature was controlled by a refrigeration unit. Tests could be conducted either under constant or varying conditions and climatic parameters could be chosen freely. Moisture flow through the structure due to diffusion and convection could be measured separately. Tests were done under shortened Nordic climate conditions from autumn to spring, see Fig. 3 right.

The comparison of simulations and accurate laboratory measurements showed good agreement (Fig. 4), which confirms the matching of the calculation results for the simultaneous spread of unsteady heat and moisture obtained with the help of calculation software with the results of laboratory tests. In the light of the above, the use of such software for the analysis of building envelopes as well as for the assessment is considered reasonable in the course of the research work.

3. Results

3.1. Influence of thermal transmittance on the risk of mould growth

It is common engineering practice that the thermal transmittance of the building envelope is regulated by the thickness of the insulation layer without large changes in other materials. The current study shows that in the current climate conditions of Estonia, an increase of insulation thickness without any actions with other existent material layers in structure, adversely changes the hygrothermal performance of the highly insulated building envelope. Fig. 5, where the materials' initial moisture content corresponds to their equilibrium moisture content at RH = 80% of ambient air, demonstrates the dependence of the RH and mould index M between the wind barrier and the insulation surface (at point A1, Fig. 1) on the thermal transmittance of the exterior wall with mineral wool insulation. On the Fig. 5 (left), it is shown that a slightly higher RH and longer drying out period was found in walls with lower thermal transmittance when the only changed parameter was the thickness of the insulation. Even though the wall with thermal transmittance $U = 0.17$ W/(m^2 K) was designed to meet the determined mould index criterion $M < 1$, by increase of the insulation thickness, the mould growth risk increased noticeably (i.e. $M > 1$), see Fig. 5 (right).

Cellulose insulation is another commonly used insulation material for timber frame structures in addition to mineral wool in low-energy building practice. Cellulose insulation is commonly installed by dry technology for horizontal structures (floor), while for vertical structures (walls) usually wet installation technology is applied, where cellulose insulation fibres are mixed with water before installation. With wet installation technology, initial moisture content of insulation is higher, which increases the drying out period and a risk of mould growth. Drying out period is longer for walls with lower thermal transmittance, see Fig. 6 (left). Similar moisture content of materials with case on Fig. 5 (initial RH = 80%), except higher water content of wet cellulose insulation (equal to RH = 97%) causes a longer drying out period and higher risks for mould growth as well, see Fig. 6 (right).

In addition to the capability of structures to dry out built-in moisture, the moisture safety of structures can be analysed also by higher moisture loads. Therefore, in addition to initial humidity in

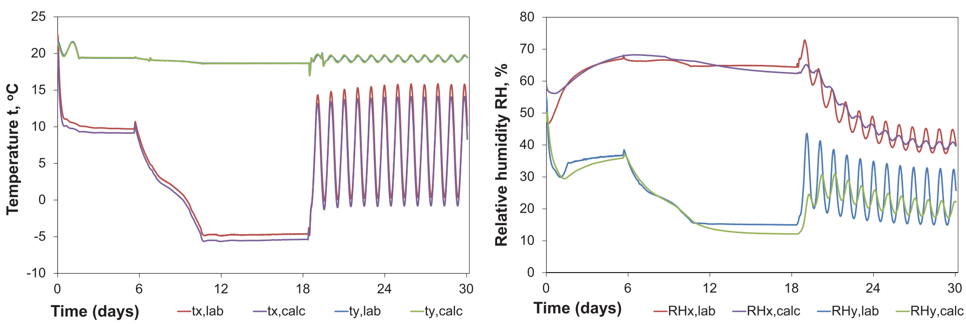

Fig. 4. Temperature (left) and RH (right) laboratory measurements (lab) and simulations (calc) of two comparison points, shown in Fig. 3.

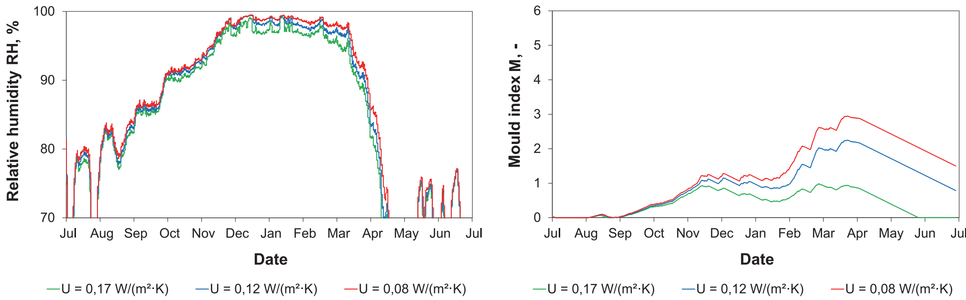

Fig. 5. The dependence of RH (left) and mould growth risk (right) on thermal transmittance. Insulation: mineral wool. Initial RH=80% of ambient air.

preceding cases (RH=80%), we also analysed the influence of the decrease of thermal transmittance on the performance of insulation when ambient air initial RH=90%, see Fig. 7. Lower thermal transmittance extends the drying out period remarkably. Higher initial moisture content has a much stronger influence on the hygrothermal performance of an exterior wall with cellulose insulation. RH performance of a wall with mineral wool insulation remained almost similar with preceding case, where initial moisture was RH=80%, see comparison of Fig. 5 (left) and Fig. 7 (left above), but the mould growth risk was higher on lower thermal transmittances in the current example, see Fig. 5 (right) and Fig. 7 (left below).

The influence of decrease of thermal transmittance on the risk of mould growth in building envelope was also analysed with uniform convection, representing the air leakage rate $q_{50}=0.6\ h^{-1}$ (see Fig. 8). Both – the wall with mineral wool (Fig. 8 left) and with cellulose insulation (Fig. 8 right) showed the tendency that mould growth risk is going up with the decrease of thermal transmittance. However, compared to case without convection (see Fig. 7), the mould growth risk increases more in relation with lower thermal transmittance walls.

3.2. Influence of selection of wind barrier materials on the risk of mould growth

Fig. 9 shows the dependence of the mould index *M* on the thermal transmittance of the exterior wall with mineral wool (left) and dry cellulose insulation (right) with different wind barrier materials, in some cases, if needed, with additional 25 mm higher density mineral wool layer on wind barrier's external side (see "+ MW 25 mm" in Figs. 9 and 10). In these cases, on Fig. 9, air and vapour barrier was selected so that no mould growth risk could occur ($M=1$) if thermal transmittance of the wall was $U=0.17\ W/(m^2\ K)$. The further decrease of the thermal transmittance of that wall increased the risk of mould growth between the insulation and the wind barrier (location A1, Fig. 1). This occurred because chosen air and vapour barriers with different vapour resistance properties for each wind barrier, which were effectual at thermal transmittance $U=0.17\ W/(m^2\ K)$, did not fulfil its requirements of vapour resistance on lower thermal transmittances, where $U<0.17\ W/(m^2\ K)$. On Fig. 9 (right) are shown results of wall with dry cellulose insulation, where the same wall structures are considerably more moisture-safe because of lower mould growth risk. This is mainly due to the higher moisture capacity and capillary moisture transfer properties of cellulose insulation.

This confirms that the hygrothermal performance of the timber frame exterior wall strongly depends also on the material properties of the wind barrier, where thermal resistance and water vapour permeability are the most important parameters. Higher water vapour permeability allows the moisture to be dried out from the wall structure more efficiently. Higher thermal resistance increases the temperature between the insulation and the wind barrier and thus decreases the RH. If the initially designed wind barrier is replaced with another material (i.e. with other thermal and water vapour resistance), the hygrothermal performance of the whole structure may decrease. This situation may occur during construction works when the initially designed wind barrier will be changed without evaluation of hygrothermal risks.

Fig. 10 (left) shows how the moisture safe ($M<1$) exterior wall with thermal transmittance $U=0.17\ W/(m^2\ K)$ may become ineligible in terms of moisture safety because of the changed wind barrier but not-changed, i.e. not-effectual, air and vapour barrier, if $U<0.17\ W/(m^2\ K)$. The air and vapour barrier (Kraft paper type A, Table 2) remains the same in all calculation cases on Fig. 10 (left). Wall with oriented strand board (OSB) or with gypsum board wind barrier is above the critical mould index value ($M>1$). If such higher density wind barriers, e.g. wood fibreboard, gypsum board, OSB or similar are required, then it is recommended to use the

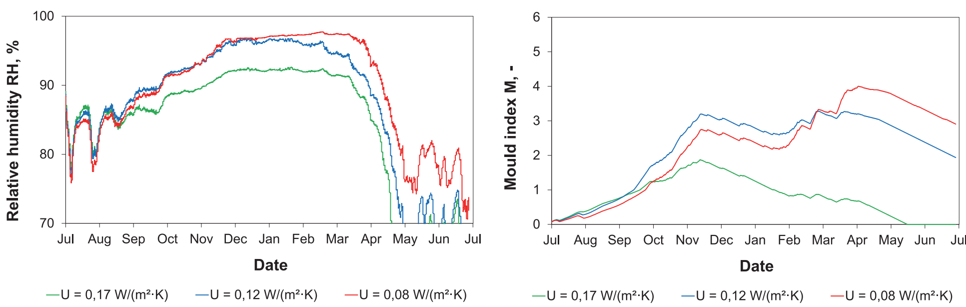

Fig. 6. The dependence of RH (left) and mould growth risk (right) on thermal transmittance. Insulation: wet installed cellulose insulation. Initial RH=80% of ambient air, for wet installed cellulose insulation RH=97%.

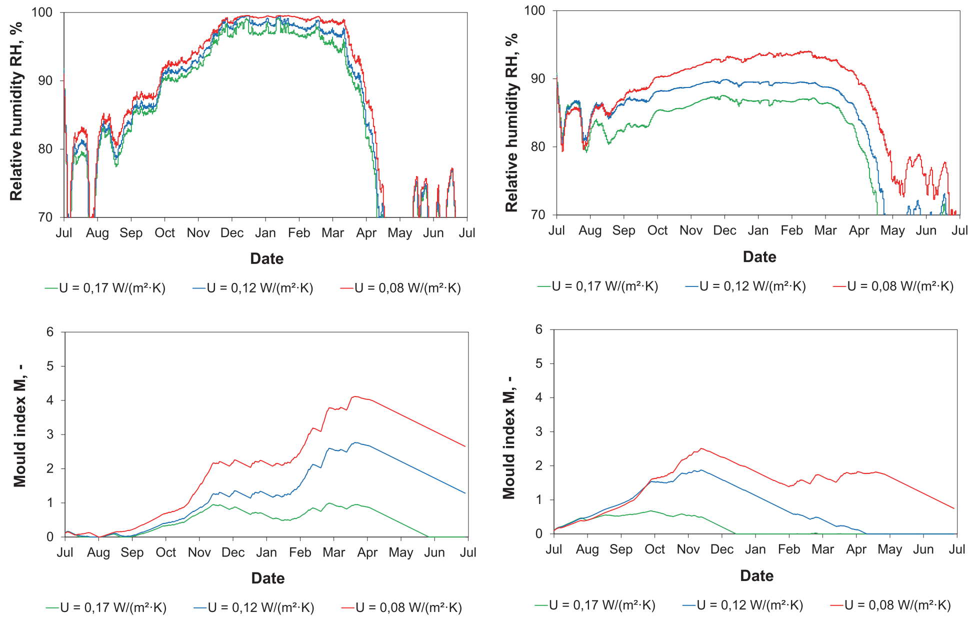

Fig. 7. The dependence of RH (above) and mould growth risk (below) on thermal transmittance. Insulation: mineral wool (left) and dry cellulose insulation (right). Initial RH=90% of ambient air.

mentioned choices on lower thermal transmittances of a building envelope ($U < 0.17$ W/(m^2 K)) only after preliminary hygrothermal analyse because of the high mould formation risk.

Fig. 10 (right) demonstrates the dependence of the required total thermal resistance of wind barrier and vapour permeability of air and vapour barrier layers to ensure a wall with no mould growth risk ($M < 1$). 22 mm wood fibreboard, 12 mm OSB or 9 mm gypsum board wind barrier with additional insulation layer (if needed) on the external side was used, to ensure (required by moisture-safety point of view) minimum thermal resistance of wind barrier's layer, for walls with different thermal transmittances. Common air and vapour materials were used, described here via their equivalent air layer thicknesses (S_d=0.1–30 m). Appeared that vapour barriers with relatively high vapour diffusion permeability are not always acceptable on lower thermal transmittances of a building envelope without additional insulation on wind barrier's external side.

4. Discussion

Performed hygrothermal simulations showed – this is also demonstrated by other authors from cold climate countries [27–29] – that a careful selection of materials makes it possible to design timber frame exterior walls that are moisture safe and provide low thermal transmittance. Therefore, timber frame structures are prospective for future nZEB. Hygrothermal performance of the timber frame exterior wall was found to be dependent most of all on the thermal resistance of the wind barrier and vapour permeability of the wind barrier and vapour barrier. When the thermal transmittance of the timber frame exterior wall is decreased only by increasing the thickness of insulation, the risk of mould growth increased. The increase of mould growth risk in the course of the lowering of the thermal transmittance was lower for some wind barriers – these materials can be described by higher thermal resistance and water vapour permeability. Thus, the building envelope of a future nZEB needs careful hygrothermal

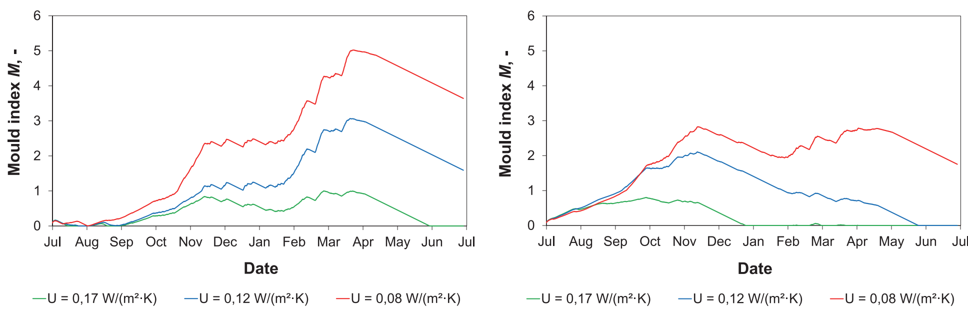

Fig. 8. The dependence of mould growth risk on thermal transmittance with influence of convection (air leakage rate q_{50}=0.6 m^3/(h m^2)). Insulation: mineral wool (left) and dry cellulose insulation (right). Initial RH=90% of ambient air.

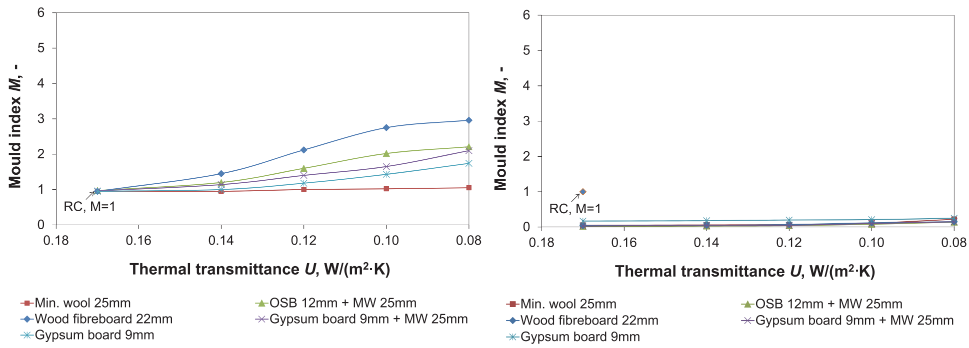

Fig. 9. The dependence of mould growth risk on wind barrier and thermal transmittance, when air and vapour barrier, shown by equivalent air layer thickness, is different for each wind barrier (S_d=0.1–15 m). Insulation: mineral wool (left) and dry cellulose insulation (right). Initial RH=80% of ambient air.

design, and material replacement during the construction works without re-calculations of the designed solution should not be allowed.

In the comparison of insulation materials – mineral wool and cellulose insulation – the cellulose insulation showed lower mould growth risk than mineral wool in conditions where other materials of envelope remained unchanged. This was mainly due to higher moisture capacity and capillary moisture transfer properties of cellulose insulation. Andersen et al. [29] showed a tendency that the moisture content behind wind barrier, measured in the north-facing facade element with mineral wool (stone wool), was higher than in the facade element insulated with cellulose insulation. Therefore, capillary transport properties and moisture capacity of wood and paper based materials should be exactly known.

Parameter analysis (thickness, water vapour permeability and thermal conductivity) indicated that moisture dry-out capability and water vapour permeability of the insulation material had the strongest influence on the RH between the insulation and the wind barrier surface in comparison of mineral wool and cellulose insulation. Higher moisture diffusivity allows inward moisture dry-out and reallocation by capillary forces. Higher moisture storage helps to survive shorter periods with high hygrothermal loads. Nevertheless, when the insulation with moisture capacity has become wet, the drying out period is longer than for materials with low moisture storage properties. Hence, higher moisture storage properties have both positive and negative aspects that should be taken into account in the design of the structures.

It is shown by many studies [30–32] that convection influences the hygrothermal performance of the building envelope. However, the airtightness as one source of convection of the building envelope is one of the key factors to achieve the energy targets of the future nZEB. As many studies have shown [23,33,34], low air leakage rate of the building envelope is reachable and we may expect the realisation of these targets.

The current study showed that convection has its role on the moisture transport, which leads to higher moisture loads in the insulation and may cause increase of mould risk above settled limit (i.e. $M>1$). It can be prevented by the weighted choice of air and vapour barrier and wind barrier hygrothermal properties – air and vapour permeability and thermal resistance.

The analysis showed the walls with non-hygroscopic insulation, low thermal transmittance and with higher density wind barrier layers to be more sensitive to mould growth. Dense wind barrier's thermal resistance (e.g. gypsum board or OSB, R=0.05–0.10 m^2 K/W) is not as high as the needed minimum of thermal resistance for wind barrier layer in order to maintain mould risks of highly insulated wall below the limit ($M<1$). Also thermal resistance of wood fibreboard (R=0.44 m^2 K/W) is not sufficient, when air and vapour barrier layer's equivalent air layer thickness $S_d<5$ m (see Table 3). On these cases additional insulation layer on the external side (e.g. high density mineral wool) of the wind barrier is installed, to secure the hygrothermally safe thermal resistance of the wind barrier layer (in most cases $R>0.4$ m^2 K/W for walls with non-hygroscopic insulation). The same limits are also described in previous researches [35].

Mundt-Petersen [35] noticed that several unexpected leakages, caused by driving rain, could penetrate deep into the different

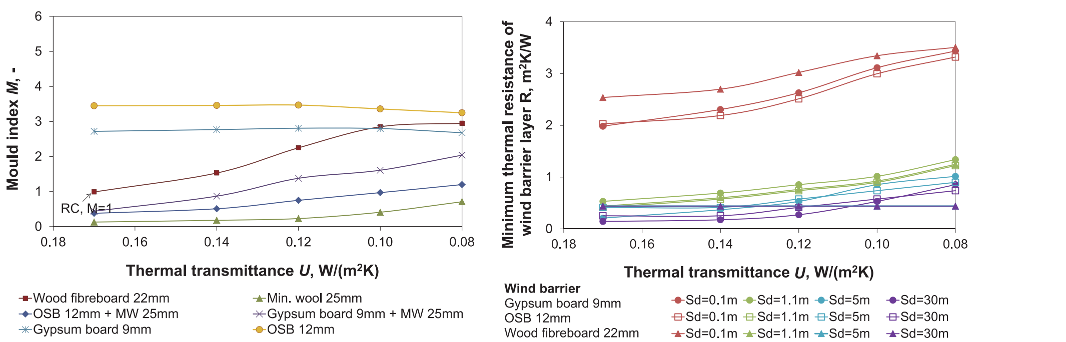

Fig. 10. The dependence of mould growth risk on thermal transmittance of a wall with different wind barriers, when air and vapour barrier, shown by equivalent air layer thickness, is the same for all cases (S_d=1.1 m) (left). The required minimum thermal resistance (R, m^2 K/W) of a wind barrier's layer of walls with common air and vapour materials, shown by their equivalent air layer thicknesses (S_d, m), if mould index $M<1$ (right). Insulation: mineral wool. Initial RH=80% of ambient air.

Table 3
Required minimum thermal resistance (R, m^2 K/W) of a wind barrier's layer of walls with common air and vapour barrier materials, shown by equivalent air layer thicknesses (S_d, m), if mould index $M < 1$.

Wind barrier (mm) (see data in Table 2)	Air and vapour barrier S_d (m)	Thermal transmittance of wall U (W/(m^2 K)) **insulation: mineral wool**					Thermal transmittance of wall U (W/(m^2 K)) **insulation: cellulose insulation**				
		0.17	**0.14**	**0.12**	**0.10**	**0.08**	**0.17**	**0.14**	**0.12**	**0.10**	**0.08**
Wood fibreboard	0.1	2.54	2.70	3.02	3.34	3.50	0.44	0.44	0.44	0.44	0.44
22 mm+HD mineral	1.1	0.44	0.60	0.76	0.92	1.25	0.44	0.44	0.44	0.44	0.44
wool layer	5	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44
	30	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44
Wind barrier gypsum	0.1	1.98	2.31	2.63	3.11	3.43	0.05	0.05	0.05	0.05	0.05
board 9 mm+HD	1.1	0.53	0.69	0.85	1.02	1.34	0.05	0.05	0.05	0.05	0.05
mineral wool layer	5	0.21	0.37	0.53	0.85	1.02	0.05	0.05	0.05	0.05	0.05
	30	0.14	0.18	0.27	0.53	0.85	0.05	0.05	0.05	0.05	0.05
Chipboard (OSB)	0.1	2.03	2.19	2.51	3.00	3.32	0.25	0.25	0.25	0.25	0.25
12 mm+HD mineral	1.1	0.41	0.58	0.74	0.90	1.22	0.25	0.25	0.25	0.25	0.25
wool layer	5	0.41	0.41	0.58	0.74	0.90	0.25	0.25	0.25	0.25	0.25
	30	0.25	0.25	0.41	0.58	0.74	0.25	0.25	0.25	0.25	0.25

wooden frame walls from the side of the air gap. Therefore, future studies should concentrate also on the detailing of external boarding.

The hygrothermal analysis of this study is based on the cold climate in Estonia. Field measurements [36–38] have shown that typical household activities and performance of ventilation provide higher moisture content indoors compared to outdoors. Therefore, the water vapour diffusion and convection are directed from indoors to outdoors and hygrothermally the most critical zone is between the wind barrier and the insulation layer [39]. For milder Central-European countries or climate, where the movement of moisture in structures is towards to the other direction, the influence of the change of the thermal transmittance on the moisture safety of the structures should be investigated separately.

5. Conclusion

A timber frame exterior wall with different thermal transmittances and material combinations was analysed by hygrothermal simulations to find out the moisture extent and the influence the increase of the thermal insulation has on the hygrothermal performance of the building envelope. The risk of mould growth was used as the performance criterion to predict the acceptability of the hygrothermal performance.

Hygrothermal simulations, with and without impact of convection, indicated that with all studied insulation materials and wind barriers it is possible to keep the mould index level $M < 1$ and thus help to ensure moisture safety of highly insulated building envelopes. It is very important to design properly the combination of thermal and vapour resistance of wind barrier, vapour and air resistance of vapour barrier, as well as the moisture capacity of insulation and wind barrier to limit the excessive humidity caused by convection and vapour diffusion.

Due to the higher RH, a higher risk for mould growth was found between the insulation and the wind barrier in walls with lower thermal transmittance, when the thickness of the insulation was the sole modified parameter. With wind barriers that have a higher thermal resistance and water vapour permeability, the increase of mould growth risk in the course of reduction of the thermal transmittance of the building envelope was lower. When the wind barrier has low thermal resistance and vapour permeability, it may need an additional thermal insulation to minimise mould formation risks in the contact surface of wind barrier and insulation layer. The drying out time of constructional moisture was longer for walls with lower thermal transmittance, causing also a higher risk for mould growth. The results of insulation material comparison revealed that the structure has lower mould index with cellulose insulation than with mineral wool, when other materials remained unchanged. In conclusion, the building envelope of the future nZEB needs more careful hygrothermal design and thorough consideration of different material properties. Interaction has decisive importance in the process of design and construction works at the building site. Engineers and designers should include hygrothermal modelling into design practice to assure the moisture safety of structures and sustainability of nZEB in the long term.

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22-24 August 2016, Technical University of Denmark, Lyngby, Denmark

POTENTIAL OF MOISTURE DRY-OUT FROM CONCRETE WALL IN ESTONIAN CLIMATE

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Abstract

The efficient way to meet the nearly zero energy buildings (nZEB) design ideology – remarkable reduction of heat losses – is to build highly insulated buildings. This study observes the hygrothermal performance of prefabricated concrete large panel element of a multi-storey building, planned to be renovated according to nZEB requirements. The validated calculation program Delphin was used to calibrate the calculation model. On the basis of measured data, the model was calibrated and calculations were made to evaluate the hygrothermal risks. The analysis showed that the hygrothermal performance of concrete wall is most dependent on constructional moisture content, dry-out capability and wind-driven rain load as well as on the N-E-S-W orientation of the wall. The results showed the highest moisture content in the wall's external concrete slab on south-west direction in the last quarter and the first months of the year, when the moisture content was 110-114 kg/m^3. This study showed that in the design of highly insulated concrete walls in cold and humid climate it is important to properly evaluate the initial state of constructions and consider critical weather loads in order to determine the feasible hygrothermal performance.

1. Introduction

The energy efficiency and overall condition improvement of apartment buildings is receiving more attention, supported by global agreements and European Union (EU) legislation with local activities. In Estonia this is one of the target actions concerning the fulfilment of energy efficiency improvement expectations as 65% of people in Estonia live in apartment houses. There are 264,000 dwellings in Estonia with a total net area of 66,692·10^3 m^2. Nearly half of these buildings, constructed between 1961-1990, are built of prefabricated concrete large panel elements where the thermal transmittance of original external walls is U=0.8-1.2 W/(m^2·K), which is 4-5 times higher than what is considered reasonable today. The designed service life of this type of buildings was 50 years, which is almost over for formerly built houses and therefore complex decisions have to be made and actions taken, but there are also many risks to consider. The entire building envelopes need deep renovation.

Kuusk and Kalamees [1] have shown that thermal transmittance of large panel apartment buildings' envelope is feasible to reduce down to U=0.15 W/(m^2·K) but ~300 mm of insulation has to be installed on the external envelope. Vinha *et al.* [2], Fedorik *et al.* [3], as well Pihelo and Kalamees [4] have pointed out that decreasing of thermal transmittance of the building envelope could increase the risk of mould growth in highly insulated buildings.

Longer constructional moisture dry-out time and capabilities are weakening the hygrothermal condition of the entire building envelope. Therefore, it is needed to pay special attention to the hygrothermal performance and moisture safety of the design and building processes of highly insulated buildings. In this study the potential of moisture dry-out from the prefabricated concrete large panel wall in Estonia was analysed to collect data for further nZEB design and renovation of that type of buildings.

2. Methods

2.1. Description of the building type

The building type studied is a five-storey house of flats, constructed from typified prefabricated concrete large panel elements, with thermal transmittance U=1.0 W/(m^2·K) (Figure 1). The panel consists from 3 sections: 60 mm external reinforced concrete slab + 120 mm wood-chip insulation layer + 70 mm internal reinforced concrete slab. The typical height of panels is 2750 mm and the width varies depending on the dimensions of rooms. The panel covers the area of external wall of one room as one part, all joists and conjunctions are filled with mortar. The external concrete slab is covered with gritstone on the outside, inside panels are plastered and finished with paint or wallpaper.

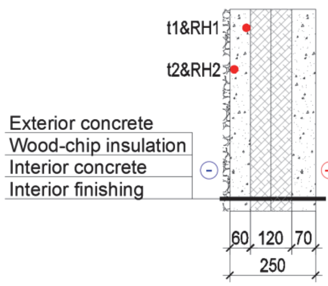


Figure 1. Overview of the typified multi-storey prefabricated concrete large panel element.

It is intended to perform a deep renovation of a building, which has been made of prefabricated concrete large panel elements, as an Estonian pilot for the EU funded project of developed and advanced prefabrication of innovative, multifunctional building envelope elements for modular retrofitting and connections [5].

2.2. Simulations

The dynamic hygrothermal simulation program Delphin, which was developed at the Technical University of Dresden and validated [6,7], was used in this study. Delphin is a simulation program for coupled heat, moisture and matter transport in porous building materials and it is used for different applications, e.g. calculation of mould growth risks with consideration of climate impacts, radiation, wind-driven rain, structure conditions and materials modelling.

The calculation model was calibrated with help of measurement data from previous comparable project [8] where hygrothermal data of typical concrete wall (Figure 1, points t1&RH1 and t2&RH2) was collected for 2 years. Initial moisture content of the building materials, which was used in the calculations (Table 1), was equal to the measured equilibrium moisture content of materials used in the calibration model (initial temperature 12°C and relative humidity (*RH*) 70%). Calculations were in good agreement with the measured data (see Figure 2 and Figure 3), therefore the model is used for further research in this study.

Table 1. Properties of materials of studied structure.

	Density ρ, kg/m³	**Thermal conductivity** λ, W/(m·K)	**Open porosity** m³/m³	**Moisture storage function** ψ, m³/m³				**Water vapour resistance factor** μ, -
RH, %				33	55	83	97	80
Concrete panel	2320	1.50	0.14	0.02	0.04	0.06	0.11	41
Wood chip insulation	500	0.14	0.93	0.01	0.02	0.03	0.06	3.80

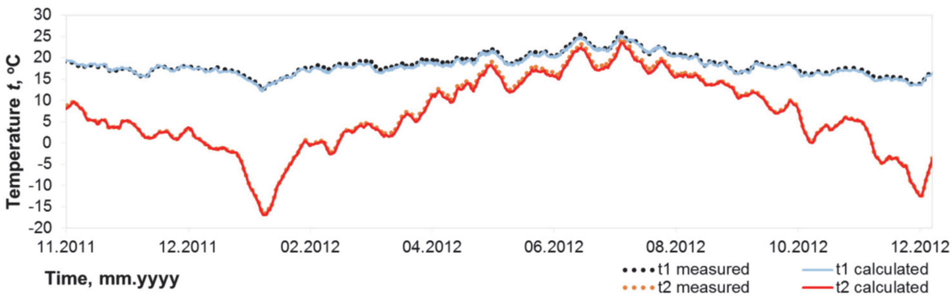


Figure 2. Measured and calculated data of temperature in wall (points t1 and t2).

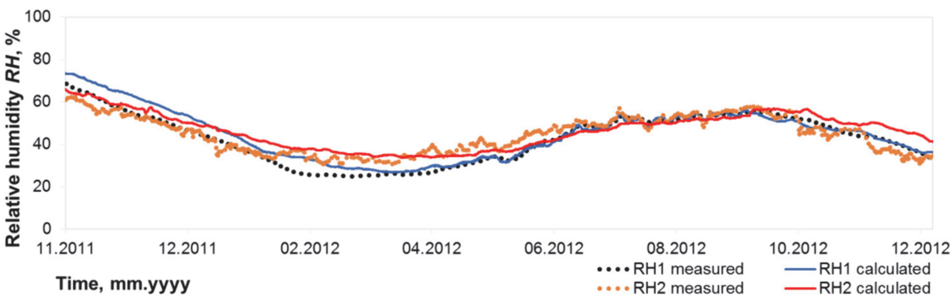


Figure 3. Measured and calculated data of *RH* in wall (points RH1 and RH2).

2.3. Boundary conditions

For the assessment of potential of moisture dry-out, 43 years (1970-2012) hourly data of the hygrothermal characteristics of Estonia was applied for outdoor climate – vertical rain flow density on the horizontal area, radiation, wind velocity and direction, outdoor *RH* and temperature. Indoor climate measurements from Estonian dwellings [9–11] were used for the determination of critical indoor hygrothermal conditions.

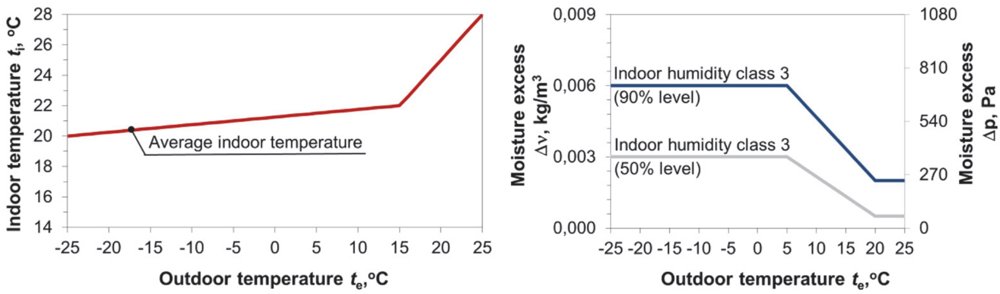


Figure 4. Dependency of indoor temperature (left) and design value of moisture excess (right) on the outdoor temperature.

For simulations, the following conditions were used: average indoor temperature, which was dependent on the outdoor temperature (Figure 4 left) and 90th percentile of indoor humidity of class 3, representing dwellings with high humidity load (Figure 4 right) and high occupancy according to national appendix of EVS-EN 15026 [12], which was expressed as indoor moisture excess Δv (kg/m^3).

Impact of wind-driven rain was taken into account according to EVS-EN ISO 15927-3 methodology [13]. Eq.1-Eq.3 characterises the calculation model of wind-driven rain to vertical wall surface:

$$I_A = \frac{2}{9}\frac{\sum v\, r^{8/9} \cos(D-\theta)}{N} \tag{1}$$

$$I_{WA} = I_A C_R C_T O W \tag{2}$$

$$C_R(z) = K_R \ln(z/z_0) \tag{3}$$

where I_A is airfield annual index (l/m^2), ν is hourly mean wind speed (m/s), r is hourly rainfall total (mm), D is hourly mean wind direction from north (deg), θ is wall orientation relative to nord, N is number of years of available data, I_{WA} is wall annual index (l/m^2), C_R is roughness coefficient, C_T is topography coefficient, O is obstruction factor, W is wall factor, K_R is terrain factor, z is height above ground, z_0 is roughness length. In our calculations, values and coefficients were used as follows: K_R=0.24 (terrain category IV), z=16 (height above ground), z_0=1 (terrain category IV), C_T=1 (no upwind slope), O=0.3 (distance of obstruction from wall < 15 m), W=0.5 (wall factor for building with flat roof, for top 2.5 m).

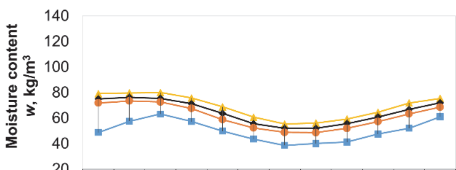
3. Results

3.1. Assessment of critical periods of moisture load and N-E-S-W orientation of a walls

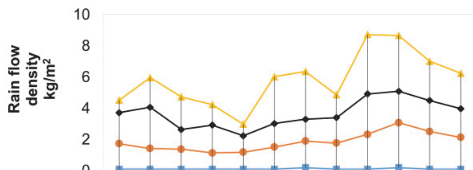
The initial examination of structures was done in 4 main orientations – north, east, south and west. At this stage the moisture content *w* (kg/m^3) was calculated for the entire studied period of 43 years for different orientations of walls on a monthly basis, without taking into account the impact of wind-driven rain.

The results showed the highest moisture content in external concrete slab to occur in the last quarter and the first months of the year. 90th percentile values of moisture content went up to 76 kg/m3 and maximum values up to 80 kg/m^3 (Figure 5 left).

The rain flow density to the surface was calculated correspondingly (Figure 5 right) where the values were highest at the last quarter of a year, starting from September and going up to 8.7 kg/m^2 while calculated 90th percentile values were 5.1 kg/m^2.



Month	01	02	03	04	05	06	07	08	09	10	11	12
Max. level	79	80	80	76	69	61	55	56	59	65	72	75
90% level	75	76	75	71	64	56	52	52	56	61	67	72
Average level	72	73	73	68	59	52	49	49	52	57	63	69
Min. level	49	57	63	57	50	44	39	40	41	47	52	61



Month	01	02	03	04	05	06	07	08	09	10	11	12
Max. level	4.5	6.0	4.7	4.2	3.0	6.0	6.4	4.9	8.7	8.7	7.0	6.2
90% level	3.7	4.1	2.6	2.9	2.2	3.0	3.3	3.4	4.9	5.1	4.5	4.0
Average level	1.7	1.4	1.4	1.1	1.2	1.5	1.9	1.8	2.3	3.1	2.5	2.1
Min. level	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.2	0.1	0.1

Figure 5. Moisture content in external concrete slab without wind-driven rain impact (left) and rain flow density to the surface (right) in south direction during the studied period (1970-2012).

The analysis was continued with the evaluation of impact of wind and rain to constructional moisture content. In Figure 6, the prevalent directions of wind and rain in the months with the highest moisture content during the studied period (1970-2012) in different orientations are shown.

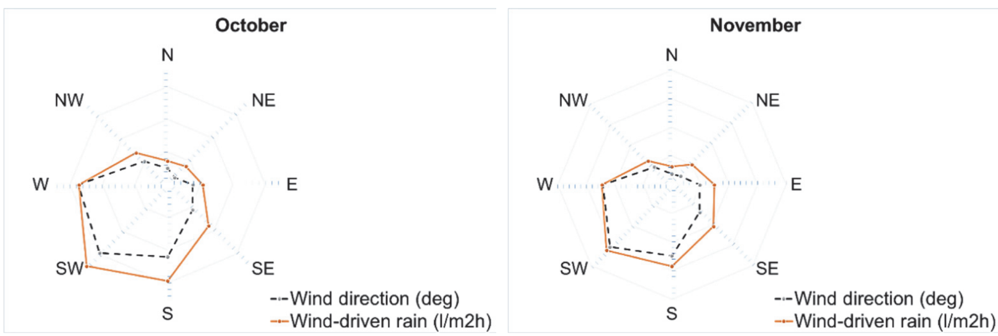


Figure 6. Schematic of prevalent directions of wind and wind-driven rain in the autumn months with the highest moisture content during the studied period (1970-2012).

The calculation results showed higher influence of wind-driven rain to hygrothermal performance of a wall on western and southern sides of the building – the maximum moisture content there was about 15-20% higher than on northern and eastern sides. At the same time the annual tendency of moisture load remained the same as in the previous phase – the most critical periods were the last quarter and the first month of the year (see Figure 7).

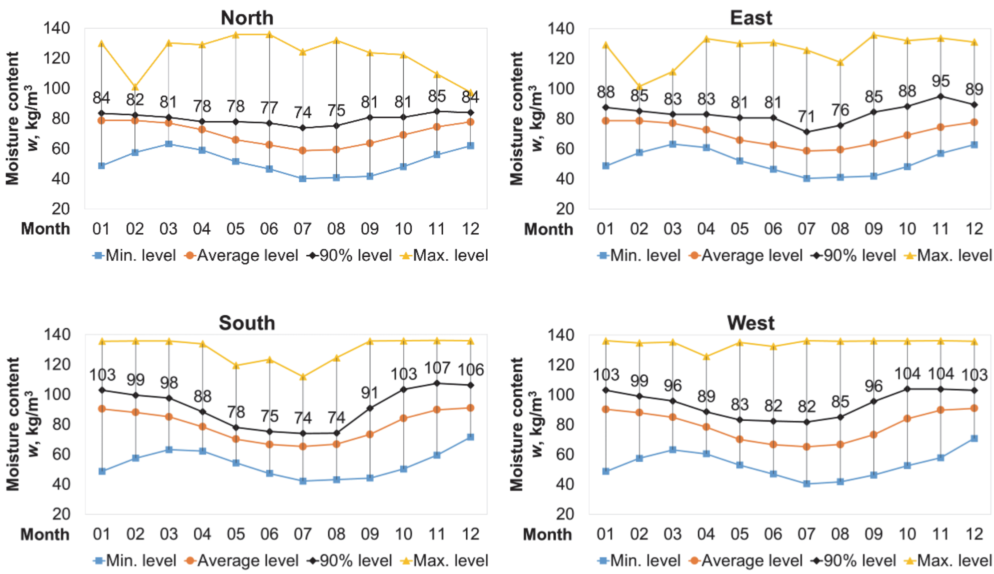
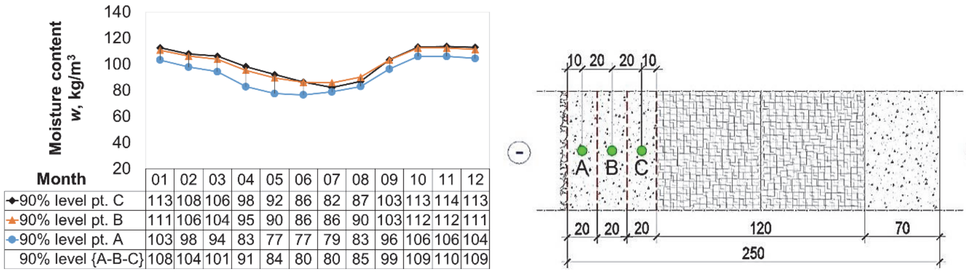


Figure 7. Monthly distribution of moisture content for external 60 mm concrete slab in different orientations with wind-driven rain during the studied period (1970-2012).

In the period studied (1970-2012) the moisture content extent over the hygroscopic range (~136 kg/m^3) in south orientation was observed for 10 years and in west orientation for 12 years in the autumn and winter periods, which provides high level of probability of full saturation to appear in external concrete slab on that period of the year.

Subsequently the moisture load analysis was continued with south-western wall as the most critical, where according to Figure 6 the prevailing wind-driven rain load was the highest and the external concrete slab moisture content in different zones (see Figure 8 right) was analysed. Figure 8 (left) illustrates the 90th percentile of each calculated point (A, B and C) and 90th percentile of the entire external slab moisture distribution in south-western side. The highest 90th percentile level of moisture content (114 kg/m^3) was at 20 mm inner zone, calculated in point C in November.



Month	01	02	03	04	05	06	07	08	09	10	11	12
90% level pt. C	113	108	106	98	92	86	82	87	103	113	114	113
90% level pt. B	111	106	104	95	90	86	86	90	103	112	112	111
90% level pt. A	103	98	94	83	77	77	79	83	96	106	106	104
90% level {A-B-C}	108	104	101	91	84	80	80	85	99	109	110	109

Figure 8. Monthly distribution of moisture content for external concrete slab in south-western orientation with wind-driven rain in points A, B and C (left) during the studied period (1970-2012) and schematic layout of zones and calculation points A, B and C (right) in external concrete slab section of wall (see Figure 1).

In Figure 9 (left) is shown the correlation of moisture content for external concrete slab and its dependence on wind-driven rain. The moisture content increases noticeably with the high rain load and falls consequently in dry days. In Figure 9 (right) are shown calculation results of average values and 90th percentile values of moisture content and its decrease in external concrete slab in 10 consecutive dry days after the rainfall. Results are showing variances of speed of moisture dry-out and moisture content levels in different seasons of the year. The dry-out is relatively fast within first 1-2 days after the rain and practically stops after 7-9 days. Quicker drop of moisture content is observed in conditions with higher moisture content (w>100 kg/m^3). Moisture content from the level 120 kg/m^3 in 2 days after the rainfall drops to the level 107 kg/m^3 while from the starting level 90 kg/m^3 in 2 days it drops down to the level 82 kg/m^3.

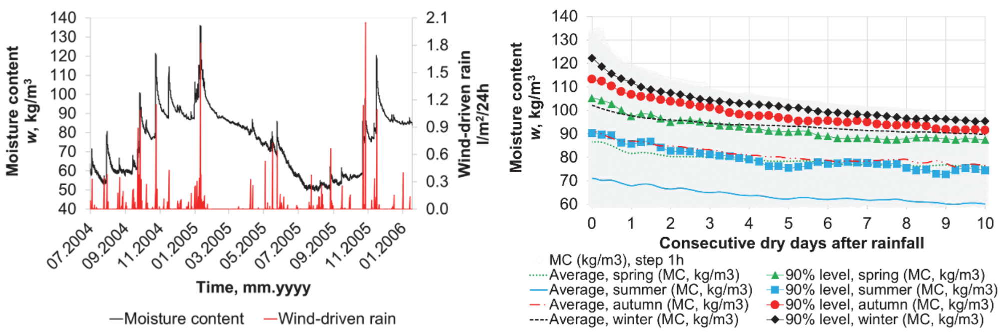


Figure 9. Correlative change of moisture content (MC) of external concrete slab in south-western orientation with wind-driven rain load (left) and moisture dry-out capability of external concrete slab (right) during the studied period (1970-2012) in consecutive 10 dry days after the rainfall in different periods of a year.

4. Discussion

With the analysis of typified prefabricated concrete large panel elements for a long-term period (1970-2012) it was observed that the highest constructional moisture content in the middle and inner 20-40 mm zone of external 60 mm concrete slab and the most critical to hygrothermal performance months are November, December and January. This could be explained with the moisture dry-out, diffusion and absorption phenomenon: the weather conditions (wind and sun radiation) in outer layer of external wall contribute to faster dry-out of moisture. But at the end of the year and during colder periods with heavy rains, the moisture load is higher and moisture dry-out times are longer. Therefore, the moisture will accumulate and redistribute inside the structure and risks of mould growth increase respectively. The calculations showed that during autumn and winter periods, the external concrete slab may stay close to the full saturation phase and the wall will dry out only in March-April. Longer periods of a high moisture load contribute to the corrosion processes to activate and moisture growth risk rises.

Comparison of results of moisture content with and without impact of wind-driven rain showed that in walls without impact of wind-driven rain (e.g. buildings with slope roofs and with wide eaves) the moisture content is high in the first quarter of the year and reaches maximum in March. Moisture level is relatively high in the last quarter of a year as well, which could be explained with lower radiation intensity and temperatures, hence with higher *RH*. These circumstances contribute to lower dry-out capabilities of the entire external slab.

Analysis of moisture content fluctuation and decrease verified the preceding findings in our study that most critical are the last quarter and the first months of the year, where moisture content in the concrete slab is the highest. The concrete structure is drying out after the rainfall in range 5-20 kg/m^3 in 10 days, depending on the seasonal conditions and moisture content. Therefore, because of big variability of moisture content levels and drying out times, it is essential to keep the hygrothermal analysis included at design process and in the construction phase as well.

In buildings where roof edges, eaves or other construction details do not provide protection from wind-driven rain load, the moisture load of external envelope are noticeably higher and dominating maximum is achieved during the last quarter of the year. According to Choi [14] and Blocken and Carmeliet [15], the highest loads are at the top corners of vertical wall. Therefore, it is essential to take into account higher moisture load when designing this type of buildings in order to assure hygrothermal performance in the critical areas of the external envelope as well.

The analysis also showed that the orientation of the building has its role in the structure's moisture content and consequently its dry-out capability. In Estonian climate, where south and west winds are prevailing, the moisture load is correspondingly higher in structures opened to south, south-west and west directions. Initial moisture redistribution analysis in areas with higher moisture loads has shown that inner zones may contain higher volumes of moisture and the dry-out capabilities are weaker compared to areas closer to the external surface.

To determine the up-to-date energy efficiency and nZEB demands and to insulate the concrete large panel walls, thorough calculations of moisture dry-out capabilities have to be made and proper solutions designed as the calculations in this study have shown that initial moisture content in external concrete slab is high, about 110 kg/m^3. After the installation of additional external side insulation and vapour protection layer (if any), the temperature of the outer layers of the wall will drop and its estimated *RH* level will stay most likely at level 50-60%. This means that about 40-50 kg/m^3 of water needs to dry out from the existing wall. The thermal resistance and vapour permeability in outer layers has to be high and mould growth risks have to be evaluated as an essential part of preliminary hygrothermal design process.

5. Conclusions

The design of highly insulated external envelopes is a demanding process where hygrothermal analysis has a very important role. Based on studies made, we may claim that prior to the installation of new layers onto an existing envelope, which may probably change the hygrothermal performance considerably, the designer has to examine the existing structures thoroughly and take into account not only the indoor and outdoor climate but also the consequences because of constructional moisture loads, dry-out capability and orientation of the designed structures.

The potential of moisture dry-out analysis of this study is based on the cold climate in Estonia and is exhaustive material for further hygrothermal design of buildings made of prefabricated concrete large panel elements in cold climate. The calculations in this research have shown that initial moisture content in the concrete slab with the impact of wind-driven rain and other weather conditions, orientation and seasonable factor, is 137 kg/m^3 as maximum, 110 kg/m^3 as 90th percentile and 90 kg/m^3 as average. In Estonia the moisture load to wall surface is highest in south-west direction, through October to December and in January.

However, after fulfilling the load-bearing requirements, other layers in the building envelope are frequently designed according to the required thermal transmittance and visual appearance. However, relying on the present and preceding studies, the design of hygrothermal performance of the future nZEB highly insulated building envelope, based on the common knowledge and practices may most likely appear insufficient. And at the same time, considerable change of climate conditions forces us to reassess the common practices as well.

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Influence of Moisture Dry-out on Hygrothermal Performance of Prefabricated Modular Renovation Elements

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Abstract

Renovation with prefabricated modular panels is one way to achieve high energy efficiency and quality both in production and installation processes. The 5-storey building, which is being fully renovated in Tallinn, Estonia, will be insulated with prefabricated modular renovation elements. The hygrothermal performance of the envelope was evaluated with calibrated dynamic hygrothermal simulations and with a mould index model, where calculation results were in good agreement with measured data and are therefore reliable for further research. The calculations were made to evaluate the hygrothermal risks in the building envelope and after the prefabricated modular elements were installed. The focus was on studying concrete wall's dry-out capability and the use of vapor barrier. The initial moisture content of the concrete wall and a right choice of air&vapor barrier layer has considerable impact on the entire envelope performance. As a result of this study, we claim that the risk of mould growth in this structure can be minimized, when the initial moisture content (IMC) of the existing concrete large panel element is $w \leq 55$ kg/m^3 and PE-foil as air&vapor barrier is used or when IMC is $w \leq 75$ kg/m^3 and the oriented strand board (OSB) as vapor control layer or when IMC is $w \leq 110$ kg/m^3 and smart vapor retarder (0.2 m< S_d <5 m) on the mounted modular element as vapor control layer is used, in combination with the prefabricated modular element's insulation, with high thermal resistance and vapor permeability (thermal resistance $R \geq 7.5$ m^2·K/W; equivalent air layer thickness $S_d \leq 0.5$ m), and wind barrier ($R \geq 0.8$ m^2·K/W; $S_d \leq 0.05$ m) layers. In the renovation of prefabricated concrete large panel buildings, it is possible to achieve good results and build sustainable solutions according to up-to-date requirements of nZEB in a cold and humid climate.

Peer-review under responsibility of the organizing committee of the SBE16 Tallinn and Helsinki Conference.

Keywords: nZEB prefabricated modular renovation solutions, hygrothermal performance, moisture safety, energy efficiency;

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1. Introduction

A decrease in heat losses of buildings is an obligatory demand for highly insulated and nearly Zero Energy Buildings (nZEB). With reference to EU energy performance of buildings directive (2010/31/EU) and agreements on the worldwide level, we are looking for at least a 20% reduction of energy use compared to previous decades. These expectations are driven by means of optimization of resources use, energy and time, as well as clean and healthy environment. The energy efficiency and whole improvement of condition of residential buildings has been receiving more attention as more than 70% of them are over 30 years old and about 35% are more than 50 years old [1]. In Estonia about 65% of people live in apartment buildings. The designed service life of this type of buildings is 50 years, which is almost over for formerly constructed buildings. Research of current technical conditions of Estonian old concrete element housing stock refers to satisfactory conditions in terms of load-bearing, but highlights insufficient energy performance, indoor climate and hygrothermal performance of the building envelope [2].

Designers, developers and owners are in search of innovative ways to minimize operating costs and environmental impact of buildings, while also increasing their functionality. Feasibility of these measures is still under discussion in order to find better solutions with lower investments [3–5]. Using prefabricated modular insulation elements when renovating buildings is one possible way to standardize and industrialize manufacturing processes and increase the quality [6]. Kalamees et al. [7] showed that modular insulation panels should decrease the thermal transmittance of walls to U_{wall}=0.11-0.47 W/(m^2·K) depending on the climate and national requirements in European countries.

However, designing highly insulated building envelopes is a demanding process where hygrothermal performance plays a critical role in order to reach sustainable outcomes. Many authors have pointed out that decreasing thermal transmittance of the building envelope could increase mould risk in highly insulated buildings [8–11]. Gullbrekken et al. [12] concluded that the risk for mould growth increases somewhat, but that in general, this can be prevented by making right choices when selecting materials and constructions. Nevertheless, the negative effect of a longer drying period of built-in moisture has a more pronounced effect than that of the colder outer parts of the wall. Longer constructional moisture dry-out period and obstacles of its capability weaken the whole building envelope hygrothermal condition. Therefore, it is necessary to pay special attention to the hygrothermal performance and moisture safety of the design and building processes of highly insulated buildings.

The aim of this study is to analyze the hygrothermal performance of the building envelope, made of concrete large panels and additionally insulated with prefabricated modular elements in Estonia. Purpose of this study is to provide input to further process of the hygrothermal design of nZEB and the renovation of prefabricated concrete large panel multi-storey buildings.

2. Methods

2.1. Description of the constructions

The building type studied in this research is a 5-storey apartment building, constructed from typified prefabricated concrete large panel elements (Fig. 1 left). The existing concrete panel with a thickness of 250 mm consists from 2 concrete sections and insulation layers: 60 mm external reinforced concrete slab + 70 mm wood-chip insulation layer + 50 mm phenolic foam insulation layer + 70 mm internal reinforced concrete slab. Typical height of panels is 2700 mm and the width varies depending on the dimensions of rooms. The external side of the panels is covered with gritstone, the interior side of the panels is caulk and finished with paint or wallpaper. The thermal transmittance of existing wall is U=0.9-1.0 W/(m^2·K).

It is intended to perform a full renovation of a building as an Estonian pilot in EU funded project of developed and advanced prefabrication of innovative, multifunctional building envelope elements for modular retrofitting and connections (MORE-CONNECT) [6]. In the pilot project, the building envelope will be insulated and rendered with the help of prefabricated modular renovation elements (Fig. 1, pos.B). The total thickness of modular element in the current project is 340-380 mm, depending on the surface flatness of the existing wall. To fill the unevenness and roughness of the existing surface, 10-50 mm light mineral wool as filling layer is intended to be added onto the inner side of the modular element (Fig. 1, pos.7). The timber-frame structure is filled with 265 mm mineral wool (Fig. 1, pos.4 and pos.5) in two layers (with insulation thermal resistance $R\geq7.5$ m²·K/W and equivalent air layer thickness $S_d\leq0.5$ m) and covered with 30 mm dense mineral wool wind barrier ($R\geq0.8$ m²·K/W; $S_d\leq0.05$ m). The 25 mm ventilated airgap (Fig. 1, pos.3) is covered with 8 mm finishing hardboard, which also provides a firm rain screen to the structure beneath. For protection from weather impacts during the construction process and from constructional moisture, the inner side of the module is designed to be protected with air&vapor barrier layer (Fig. 1, pos.6). The designed thermal transmittance of the external wall is U_{wall}=0.11 W/(m²·K) and the airtightness of the entire building envelope q_{50}=0.2-0.3 m³/(h·m²). To avoid the thermal bridges and minimize the impact of air leakages, smart connectors and innovative fixings, also sealants and polyurethane (PUR) foam will be used at critical joints.

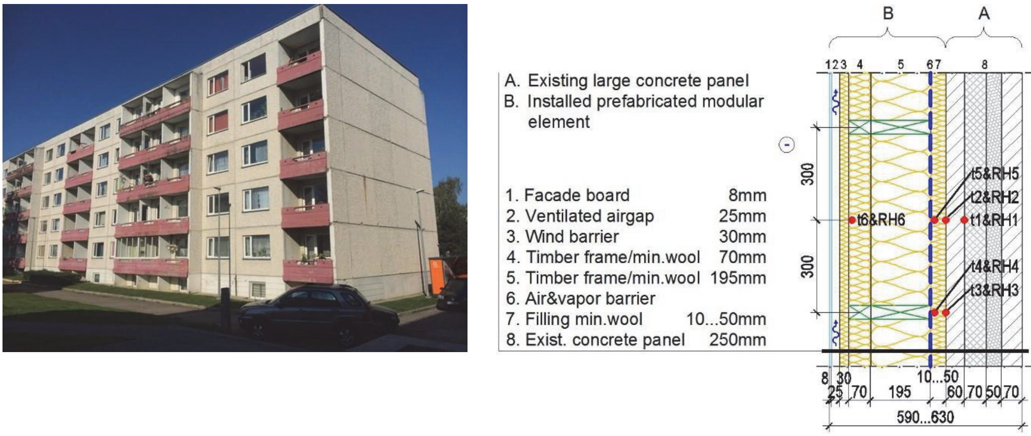

Fig. 1. Overview of the existing building before renovation (left) and solution (designed by architecture and design bureau Sirkel&Mall OÜ) of concrete large panel covered with prefabricated modular element (right).

2.2. Hygrothermal simulations

The dynamic hygrothermal simulation program Delphin, which was developed at the Technical University of Dresden and has been successfully validated [13,14], was used in this study. Delphin is a simulation program for coupled heat, moisture and matter transport in porous building materials and it is used for different applications, e.g. calculation of mould growth risks with consideration of climate impacts, radiation, wind-driven rain, structure conditions and modelling of materials.

The calculation model was calibrated with the help of measurement records from a previous, comparable project where hygrothermal data of concrete wall in points 1 and 2 (see t1&RH1 and t2&RH2 in Fig. 1 right) was collected for 2 years and then analyzed [15,16]. In the current study, the calculations were made in points 3, 4, 5 and 6 (see t3&RH3, t4&RH4, t5&RH5 and t6&RH6 in Fig. 1 right) with initiation time in November as the most critical.

In this research a mathematical model, designed in Finland [17,18], was used for the calculation of mould growth, decrease and mould index (M) in changing conditions. According to this model, in the course of fluctuating humidity conditions, the total exposure time for response of growth of mould fungi is affected by the time periods of high and low humidity conditions, as well as the humidity and temperature level. In the simulation of mould growth, it is crucial to know the lowest (threshold) conditions where fungal growth is possible on different materials. The time period that is needed for the onset of mould growth and growth intensity, is mainly dependent on water activity, temperature, exposure time and surface quality of the substrate. The boundary curve for the risk of mould growth in the range of temperature between 5 to 40°C on a wooden material can be described by a polynomial function (see Eq.1).

$$RH_{crit} = \begin{cases} -0,00267 * t^3 + 0,16 * t^2 - 3,13 * t + 100 & \text{when } t \leq 20^\circ C \\ RH_{min} & \text{when } t > 20^\circ C \end{cases} \quad (1)$$

where t is temperature on the investigated material surface (°C) and RH_{min} represents the minimum level of relative humidity (RH), where mould growth is possible (varies according to the sensitivity of the material, for example RH_{min}=80% for wood or 85% for concrete). In the current study, the critical value of the mould index was set to level M=1 (no growth, pores are not activated) according to the mould index model to avoid the formation of mould in a structure. In order to compare the hygrothermal indicators and to analyze their impact, different materials have been used in the calculations (see Table 1).

Table 1. Properties of materials in structures studied.

Material	Thermal conductivity λ, W/(m·K)	Moisture storage function w, kg/m³					Water vapor resistance factor μ, -	Density ρ, kg/m³	Open porosity m³/m³	Water absorption coefficient A_w, kg/(m²·s^0.5)
RH		33%	55%	75%	83%	97%	83%			
Concrete*	1.500	38.0	53.0	78.0	86.0	134	41.0	2320	0.14	0.0200
Wood chip insulation*	0.140	6.00	11.0	15.0	21.0	32.0	3.80	500	0.93	0.0089
Phenolic foam insulation*	0.064	0.25	0.32	0.36	0.54	0.98	2.85	30	0.90	0.0010
Timber (pine)	0.130	32.0	45.0	80.0	108	185	40.0	450	0.62	0.0155
Oriented strand board (OSB)	0.130	31.0	46.0	78.0	110	183	165	646	0.40	0.0113
Mineral wool wind barrier	0.031	0.21	0.28	0.29	0.96	3.30	1.50	104	0.90	
Mineral wool insulation	0.037	0.14	0.18	0.36	0.80	2.40	1.20	22	0.98	
Vapor barrier PE-foil	0.400						89000	980	0.001	
Smart vapor retarder (0.2 m<S_d<5 m)	0.230						800	460	0.59	0.0001

* Materials in the existing prefabricated concrete large panel element (see section A, Fig. 1 right)

2.3. Boundary conditions

The calculations in our previous research [16] have shown that the initial moisture content in the concrete facade without the wind-driven rain moisture load is w=75 kg/m³ as an average and with the impact of wind-driven rain, orientation and seasonable factor 137 kg/m³ as maximum, 110 kg/m³ as 90th percentile and 90 kg/m³ as an average. In Estonia the moisture load to wall surface, caused by wind-driven rain, is highest in south-west direction, through October to December and in January. Indoor climate measurements from Estonian dwellings [19–21] were used to determine critical indoor hygrothermal conditions. For simulations, the following conditions were used: average indoor temperature, which is dependent on the outdoor temperature (Fig. 2 left) and 90th percentile of indoor humidity of class 3, representing dwellings with high humidity load (Fig. 2 right) and high occupancy according to national appendix of EVS-EN 15026 [22], expressed as indoor moisture excess Δν (kg/m³).

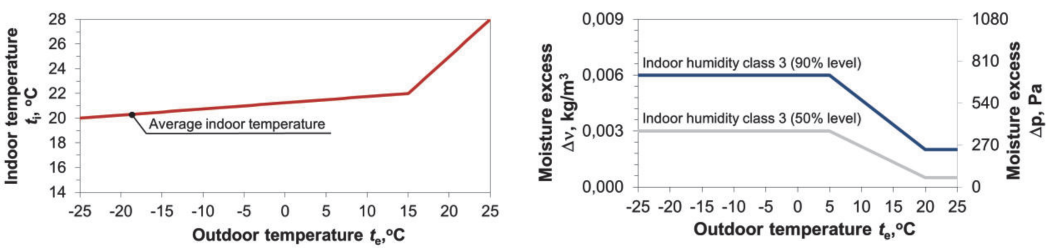

Fig. 2. Dependency of indoor temperature (left) and design value of moisture excess (right) on the outdoor temperature.

In the assessment of hygrothermal risks, the hourly data of the moisture reference year (MRY), critical to mould growth and water vapor condensation in Estonia, was applied to outdoor climate [23]. According to Estonian energy test reference year (TRY) the daily maximum at summer time is +19…+22°C, in winter period +3…+7°C; monthly average at summer time is +14…+17°C, in winter period -5…0°C and daily minimum at summer time is +8…+12°C, in winter period -14…-10°C [24].

3. Results

The initial simulation of the structure was done in points 3, 4, 5 and 6 (see t3&RH3, t4&RH4, t5&RH5 and t6&RH6 in Fig. 1 right). The initial moisture content of the existing concrete large element external slab was set to w=110 kg/m^3 as the starting state. *RH* was observed throughout a 5-year period. Initially the solution was designed so that the PE-foil was used as air&vapor barrier (Fig. 1, pos.6), serving the purpose of the basic suitable solution for timber-frame structures in cold climate conditions [25]. The highest *RH* level was found on the inner surface of PE-foil air&vapor barrier, in the location of wooden studs (in point 4, see Fig. 1). At this location the insulation was at full saturation state for more than 3½ years (see Fig. 3, P4). For more than a 1-year period, 100% of *RH* was also detected on the inner surface of the PE-foil air&vapor barrier between wooden studs (see Fig. 3, P5). In the analyzed points 3 and 6, *RH* dropped in the course of 3-4 months to the level of equilibrium state and thereupon followed normal weather dynamics (see Fig. 3, P3 and P6).

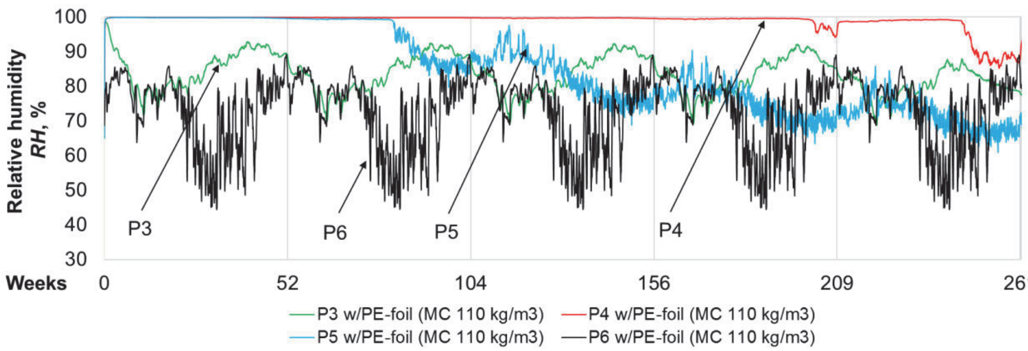

Fig. 3. *RH* in the analyzed points 3, 4, 5 and 6 with PE-foil as air&vapor barrier layer in the structure throughout 5-year period when the initial moisture content of the concrete large panel is w=110 kg/m^3.

As a result of the preceding calculations, analysis was continued in the most critical hygrothermal performance point 4 (see t4&RH4 in Fig. 1 right), on the inner surface of the PE-foil air&vapor barrier, in the location of wooden studs as the highest *RH* level in the analyzed period was observed there. In this location, the *RH* was calculated with a different air&vapor barrier and control layers and with a number of the initial moisture content levels in the external slab of existing concrete large element (75 kg/m^3, 90 kg/m^3 and 110 kg/m^3) in order to replicate the different moisture loads and at the same time, compare moisture load impact with different air&vapor control layers.

The lowest moisture load at the monitored point was detected in the solution without an air&vapor barrier layer (see Fig. 4) and the highest level was reached with the solution where the initial moisture content of concrete large element was set to 110 kg/m^3 and a PE-foil as air&vapor barrier layer was used. As a result of this stage, it was decided to continue with smart vapor retarder with changing equivalent air layer thickness (0.2 m<S_d<5 m) as vapor control layer, instead of PE-foil.

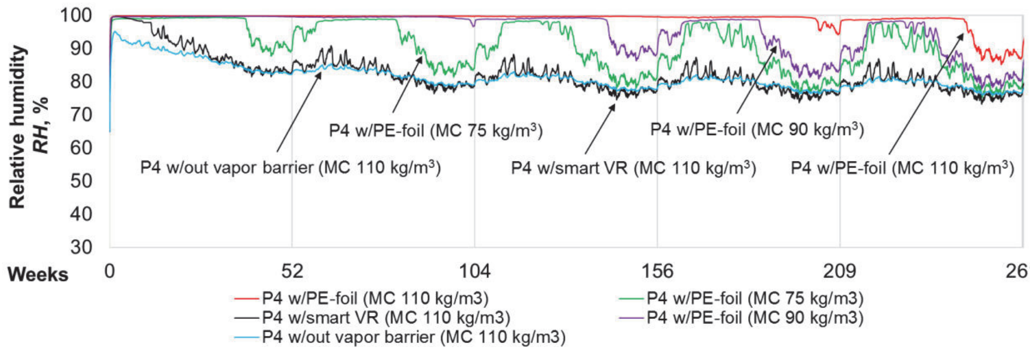

Fig. 4. *RH* on the inner surface of the air&vapor barrier, in the location of wooden studs in point 4 with the different vapor control layers and different initial moisture content (MC) of concrete large element throughout a 5-year period.

The analysis was continued with monitoring the *RH* level in the points 3, 4, 5 and 6 throughout a 2½ year period when smart vapor retarder with changing equivalent air layer thickness properties (0.2 m<S_d<5 m) as air&vapor control layer was used and the initial moisture content of the concrete large panel was w=110 kg/m^3. The *RH* level in monitored points dropped after initiation relatively quickly and reached an equilibrium state in the course of 4-5 months (see Fig. 5 left). The highest level of *RH* throughout the calculated period was observed in point 4. The overall trend of *RH* in point 6 was higher than in the first stage of simulations (see Fig. 3) and the lowest levels were detected in point 5.

The final stage of the assessment of moisture dry-out and hygrothermal performance of the structure was conducted with the calculation of mould indexes in monitored points 3, 4, 5 and 6 with the mould growth and decline model [17,18]. To the materials in the structure was initially given the rating of "very sensitive" in the sensitivity classification, which is described in the mould growth model as a class for untreated wood with lots of nutrients for biological growth. These calculations gave unsatisfactory results (i.e. M>1) in points 3, 4 and 5 (see Fig. 5 right).

At the next step the sensitivity class "sensitive" was applied, which is described as class for planed wood, paper-coated and wood-based products. In the most critical point 4 and in the point 5, the mould index exceeded the critical level (M>1).

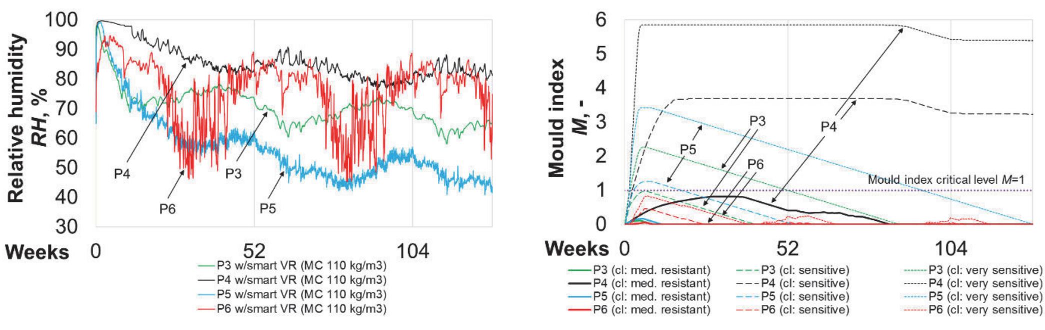

Fig. 5. *RH* in the analyzed points 3, 4, 5 and 6 with vapor retarder (0.2m<S_d<5m) when the initial moisture content of the concrete large panel is w=110 kg/m^3 (left). Calculation results of mould indexes (M) with different sensitivity classes in the points 3, 4, 5 and 6 with smart vapor retarder (0.2m<S_d<5m) when the initial moisture content of the concrete large panel is w=110 kg/m^3 (right).

Taking into account the properties of construction and materials in the analyzed structure points, the sensitivity class was switched to "medium resistant", which is the class for cement or plastic based materials and mineral fibers and describes the situation in monitored points most accurately. The mould index was recalculated and in the most critical point 4, the result obtained was under the critical level (M<1). No noteworthy mould formation in other points (3, 5 and 6) was detected as a result of this calculation stage as well.

As an alternative, the solution with oriented strand board (OSB) as a vapor retarder layer was examined instead of thin rolled vapor retarder. For the evaluation of this solution the *RH* in point 4 was observed throughout a 2½ year period and mould index was calculated with 22 mm OSB, when the initial moisture content of the existing concrete large element external slab was w=75 kg/m^3 or 110 kg/m^3. The calculation results indicated that with initial moisture content w=75 kg/m^3 or 110 kg/m^3 of concrete large element, the *RH* level in monitored point 4 dropped gradually in the course of 8-10 months to its equilibrium state, which was followed by a period of normal weather dynamics (see Fig. 6 left).

Subsequently, the mould index M was calculated with the same conditions with mould growth sensitivity class "very sensitive", following the properties of the wooden-based OSB. The results indicated that the mould index remained under the critical level (M<1) when the initial moisture content of the concrete slab was w≤75 kg/m^3, meaning basically situation without wind-driven rain load. When the initial moisture content of concrete slab was w>75 kg/m^3 then the mould index calculations gave unsatisfactory results in point 4 (i.e. M>1, see Fig. 6 right).

Mould index was calculated also with the same conditions in point 4 with originally designed solution, where PE-foil as air&vapor barrier layer was intended to use and the initial moisture content of the existing concrete large element external slab was w=75 kg/m^3, 90 kg/m^3 or 110 kg/m^3. With the stated initial moisture content levels and with all mould growth model sensitivity classes, the calculated mould index exceeded the critical level to a large extent (M>3). Calculations of the mould index in point 4, when PE-foil as air&vapor barrier layer was used, gave satisfactory results (i.e. M<1) in sensitivity class "medium resistant" only in cases where the initial moisture content of the existing concrete large element external slab was w≤55 kg/m^3. Calculations with higher sensitivity classes ("sensitive" and "very sensitive") gave unsatisfactory results (i.e. M>1) in point 4, which indicates that in this type of structure, with PE-foil (or with similar to its vapor resistance material) it is not allowed to use untreated wood and wood- or paper-based materials.

Therefore, meeting the requirements of the hygrothermal performance solution was ascertained in point 4 with smart vapor retarder with changing equivalent air layer thickness 0.2 m<S_d<5 m when the initial moisture content of existing concrete large panel was w≤110 kg/m^3 or with 22 mm OSB when the initial moisture content of the existing concrete large panel was w≤75 kg/m^3 or with PE-foil when the initial moisture content of existing concrete large panel was w≤55 kg/m^3. In all of these solutions prefabricated modular element's insulation thermal resistance was R≥7.5 m^2·K/W with equivalent air layer thickness S_d≤0.5 m and element's insulation layers were covered with 30 mm dense mineral wool wind barrier (R≥0.8 m^2·K/W; S_d≤0.05 m) and firm facade boarding.

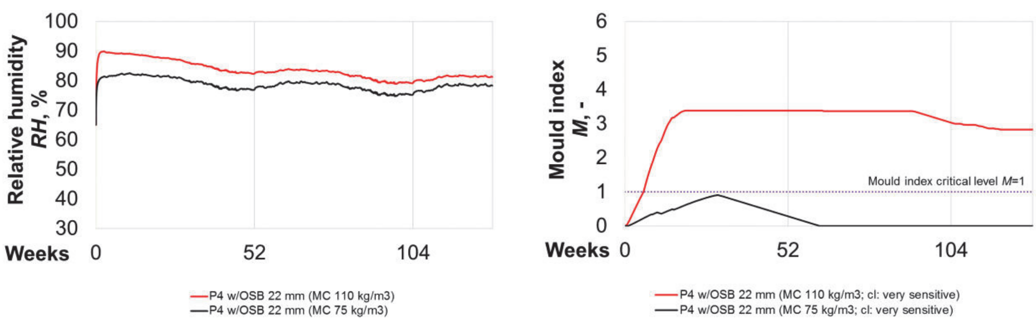

Fig. 6. *RH* in the analyzed point 4 with OSB as vapor retarder when the initial moisture content of the concrete large panel is 75 kg/m^3 or 110 kg/m^3 (left). Calculation results of mould indexes (M) with the class "very sensitive" in the point 4 with OSB as vapor retarder when the initial moisture content of the concrete large panel is 75 kg/m^3 or 110 kg/m^3 (right).

4. Discussion

In the course of the analysis of the calculation results it was confirmed that both initial moisture load and the hygrothermal properties of the air&vapor barrier materials are determinative for hygrothermal performance, particularly for the level of the mould index and changes in it. The values of the *RH* and mould index, and consequently the probability of mould formation, may vary to a very high extent in the case of walls with the same thermal transmittance when there are differences in initial moisture load as well as in air, vapor and wind barrier materials,.

Considering the fact, that it is common in cold climate that most of the year the indoor moisture load is higher than on the outside, the hygrothermal design of building envelopes should also consider the moisture flux that may penetrate into the building envelope with the direction from inside to outside and pass layers with different properties in the building structures (e.g. cracks or open junctions in the internal side of the structures). In the course of this process, unregarded moisture may accumulate in the structure's layers and cause higher moisture load and mould formation in addition to higher thermal transmittance. The calculations where PE-foil was used as an air&vapor barrier with high vapor resistance (see Fig. 3 and Fig. 4), showed that there is a very high risk of occurrence of humidity problems. Moisture volume, drying out and moving through the existing wall layers, is trapped behind the foil (see points t4&RH4 and t5&RH5 in Fig. 1) and *RH* level will stay there at the full saturation state for many years. Mould index calculation results in critical point 4 (see t4&RH4 in Fig. 1) with PE-foil as air&vapor barrier layer were in compliance with analysis results of *RH* levels and confirmed that the high initial moisture content of existing concrete element (in this case w>55 kg/m^3) will lead to extensive moisture growth. When using a vapor retarder with changing equivalent air layer thickness properties (e.g. 0.2 m<S_d<5 m), the risk of moisture accumulation in the structure is lower and the entire envelope will obtain the equilibrium moisture state in 4-5 months.

However, it is very important to note that this approach is true if outer layers (i.e. insulation and wind barrier) will not resist the moisture flow and the vapor control layer ensures the required moisture resistance. Nevertheless, sometimes there is an unavoidable need to consider alternatives. If the design or transportation restrictions of factory-made modular elements does not allow the use of thin rolled vapor retarders or rigid and a stiffening layer on modules is required, then OSB is a functional solution. As the calculations in this study have demonstrated, this solution has strict limits: during the construction works, when prefabricated modules will be installed onto the building, the initial moisture content of an existing construction must not exceed the limit w=75 kg/m^3. According to the measurements and calculations [15,16], the moisture content is about 75 kg/m^3 in existing, previously constructed and in good condition concrete elements only in the dry (not rainy) summer-time period. In the Estonian humid and cold climate conditions, starting from September and lasting until the end of April, the average moisture content in concrete elements is around 90-110 kg/m^3.

As preceding calculations have shown, there are big differences of hygrothermal performance and risks of failure when designed air&vapor barrier and/or wind barrier layers will be changed in the construction process without complementary control calculations. Many authors [8,10–12] have pointed out that in highly insulated buildings, high thermal resistance and vapor permeability of wind barrier layer are the key components of the well-functioning highly insulated building envelope. Longer constructional moisture dry-out period is worsening the hygrothermal condition of the entire building and its envelope. On the other hand, if vapor control layer is missing, then at conjunction surfaces of existing and new layers mould risk is low, but the further moisture flux cannot be controlled. It is very important to take into account and to consider the possible building technology mistakes or cracks and open joints in existing structures which allows uncontrolled moisture flow to move towards to outer layers where it may cause the problems because of moisture excess as described above. Particularly because of unknown state of existing structures and primarily because of its moisture content, this is a firm suggestion to conduct the hygrothermal measurements of existing structures before final design decisions and construction works.

Therefore, the evaluation of building state, presence and properties of the air and vapor barrier layer, preventing (or allowing) the penetration of moisture, as well as its high quality of installation, are very important on the surface of the existing concrete building envelopes in renovation process towards to nZEB. Based in this study, we may declare that the importance of that is arising if the existing structures with relatively high moisture content are covered with new thick insulation and finishing layers.

5. Conclusions

The hygrothermal performance of the building envelope, constructed of concrete large panels and covered with prefabricated modular elements in Estonia was analyzed in this research to collect data for further process of hygrothermal design of nZEB and renovation of prefabricated concrete large panel multi-storey buildings.

The most important factors for the moisture dry-out are similar to the risks related to the formation of mould and water vapor condensate. Contrariwise to the common timber-frame wall, where the PE-foil as the air&vapor barrier does not cause any serious problems to the hygrothermal performance, in modular insulation panels it prevents the constructional moisture dry-out and causes high risk of mould formation. In other words – an air&vapor barrier layer with high water vapor resistance on the surface of the moist existing structure may lead to high moisture accumulation between the installed air&vapor barrier and existing structures. The dry-out of initially moist concrete slabs, that have been insulated and covered with an air&vapor barrier layer, may take several years. The condition of existing structures and uncontrolled high indoor moisture excess load may cause unexpected moisture flux and increase humidity loads in the structure.

A functional assembly solution is presented as a conclusion of this study (see Fig. 7). This is modified alternative to initially designed solution (see Fig. 1) with remarks to important details and units from a point of view of the hygrothermal performance.

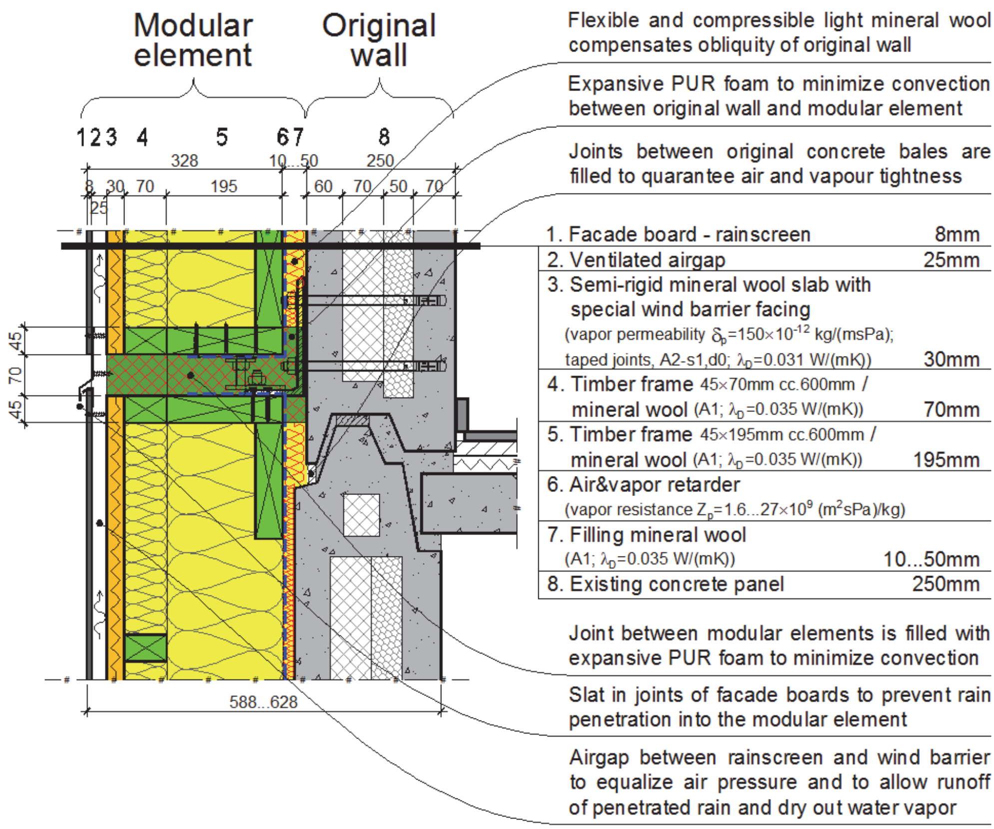

Fig. 7. Modified external wall with modular element, based on hygrothermal calculations.

Meeting the requirements of the hygrothermal performance of studied solutions was ascertained with smart vapor retarder with changing equivalent air layer thickness 0.2 m<S_d<5 m when the initial moisture content of existing concrete large panel was w≤110 kg/m^3 or with 22 mm OSB as vapor control layer when the initial moisture content of the existing concrete large panel was w≤75 kg/m^3 or with PE-foil as air&vapor barrier when the initial moisture content of existing concrete large panel was w≤55 kg/m^3.

As a result, it is possible to achieve good results and build sustainable solutions according to the up-to-date requirements of nZEB with prefabricated renovation modules on concrete large panel buildings renovation in cold and humid climate. The prerequisites there for hygrothermal performance and designing are the preliminary measurements of building state, carefully considered vapor control layer, the vapor permeability of which is controlled by hygrothermal calculations, and insulation and wind barrier layers with high thermal resistance and vapor permeability.

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nZEB Renovation with Prefabricated Modular Panels

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Abstract

The reduction of energy use in buildings is expected to be reached in part by fulfilling several requirements of the low- and nearly-zero energy buildings (nZEB) policy. The improvement of energy performance of buildings offers a huge potential for energy savings as the annual replacement of existing stock is only 1–2%. The efficient way to accomplish the purpose of the nZEB is to apply the integrated design process and application of prefabricated modular renovation elements on a large scale. In the Horizon2020 MORE-CONNECT project we developed prefabricated modular elements for the building envelope insulation and with the use of these elements, the nZEB renovation will be realized as a pilot. The study includes a complex of measures: hygrothermal measurements and analysis of moisture safety, prefabricated highly-insulated facade and roof modular renovation elements, full repair of indoor areas, rebuilding of balconies, insulation of cellar constructions, the full modernization of heating and ventilation systems. Ventilation ducts are integrated into the modular panels to minimize supply ductworks in apartments. Roof modules include solar panels and collectors for renewable energy production as well as a system for rainwater drainage. All technical systems and building modules will be equipped with monitoring systems and data will be logged periodically.

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Keywords: nZEB prefabricated modular panels; hygrothermal performance; moisture safety; energy efficiency

1. Introduction

Prefabrication of buildings has been one method to increase quality and effectiveness of construction for many decades. Development of concrete large panel systems started already before WW II and growth remained intensive in postwar period. The designed service life of this type of buildings is typically 50 years, which is almost over today

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for formerly constructed buildings. As more than 70% of residential buildings are over 30 years old and about 35% are more than 50 years old, whole technical improvement of condition has been receiving more attention [1].

Designers, developers and owners are in search of innovative ways to minimize operating costs and the environmental impact of buildings, while also increasing their functionality. Increasing energy performance has been the driving force for renovation of old prefabricated concrete large panel apartment buildings because energy related measures help to increase cost-effectiveness of the whole renovation process and the upkeep of buildings [2–4]. An innovative way of renovation is the application of prefabricated multifunctional renovation elements which has the potential to reduce costs and renovation time, reduce disturbance for occupants and, at the same time, enhance quality and performance in terms of energy efficiency, building physics and indoor climate [5–9].

Future nearly Zero Energy Buildings (nZEB) should be much more highly insulated than buildings developed some years ago [10]. The Horizon2020 project 'MORE-CONNECT' has been launched to develop energy efficiency, hygrothermal performance and aesthetics of buildings and demonstrate technologies of prefabricated modular renovation elements, including the prefab integration of multifunctional components, e.g. for climate control [11].

The aim of this study is to present design solutions of nZEB renovation of typical apartment building made of concrete large panels, constructed during the 1960-90 period in Estonia. The pilot renovation will be conducted with this solution in summer 2017. The design solution of current project will provide input to further process of the integrated design of nZEB and the renovation of prefabricated concrete large panel multi-storey apartment buildings.

2. Case study building

The building type studied is a 5-storey dormitory building with total area 4318 m^2, constructed in 1986 and analogous to mass production apartment buildings (series 111-121) from 1960-1990 (Fig. 1, left). Existing 250mm concrete panel exterior wall consists of 2 concrete sections and insulation layers: 60mm external reinforced concrete slab + 70mm wood-chip insulation layer + 50mm phenolic foam insulation layer + 70mm internal reinforced concrete slab. The existing flat roof with parapet is covered with bitumen felt and insulated with wood-chip boards. The thermal transmittance of the existing envelope is U=0.9–1.1W/(m^2·K). Calculated on base of the measurements temperature factor f_{Rsi}<0.80, which is under the accepted limit [12,13]. Because of serious thermal bridges in these type of buildings [14], mold growths on interior surface, especially in the corners of exterior walls and roof (Fig. 1, see IR1).

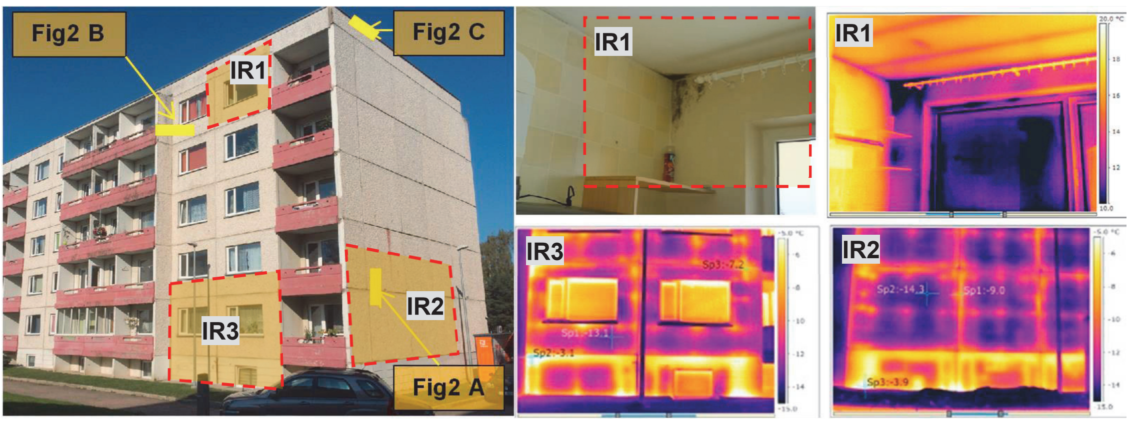

Fig. 1. Overview of the pilot building before renovation from outside (left) and with thermal camera images (right).

The pilot building has similar problems typical to many other older buildings: high energy consumption, insufficient ventilation, overheating during winter, unsatisfactory thermal comfort. Fresh air inlet was initially designed through the slits around untightened window wooden-frames and natural exhaust via kitchen and sanitary rooms to central shaft. The building has a one-pipe radiator heating system without thermostats and the room temperature for the whole building is regulated by a heat substation depending on the outdoor temperature [15]. Pre-renovation total delivered annual energy with III indoor climate category (ICC III, acceptable, moderate level of expectation) was 214kWh/(m^2·a): for heating and ventilation 149kWh/(m^2·a), for domestic hot water (DHW) 30kWh/(m^2·a), for appliances and electricity 30kWh/(m^2·a), for fans and pumps 5kWh/(m^2·a).

3. nZEB energy performance

nZEB is defined in Estonia as a numeric indicator, Energy Performance Value (EPV), of primary energy use taking into account energy for indoor climate (heating, cooling, ventilation, lighting), DHW and appliances. For nZEB apartment houses EPV<100kWh/(m^2·a) [16]. Ventilation airflow after renovation should represent a normal level of expectation for the II indoor climate category (ICC II) with ventilation airflow 0.42l/(s·m^2).

The design of the pilot started with preliminary energy and economical calculations [17,18]. The calculated primary energy use of nZEB renovation shows a 2/3 reduction. The heating system will be replaced with a two-pipe system with hydronic radiators and thermostats. The building's initial passive stack ventilation system will be replaced with a mechanical supply and exhaust ventilation with heat recovery. The deficit of places for ventilation ducts in this project design will be solved with the integration of preheated air supply ducts into the renovation module panels (Fig. 2 B). Solar collectors and PV panels will be installed onto the roof, ventilation and sewerage heat recovery is applied. However, energy cost reduction alone is not enough to make nZEB renovation profitable for a building owner [19,20].

Table 1. Energy use and on site energy production of renovated nZEB pilot (kWh/(m^2·a)).

	Energy need		Onsite energy production	
	Heat	Electricity	Heat	Electricity
Space heating and heating of ventilation air with heat recovery (VHR)	10			
Domestic hot water (production: solar collectors, sewerage heat recovery)	30		15+8	-4
Appliances and lighting (production: solar panels)		30		2
Fans, pumps		10		
Total (delivered energy)	40	40	23	-2
Total primary energy use (with weighing factor for electricity=2.0 and for district heating=0.9)	116		17	

4. Prefabricated modular panels for additional thermal insulation of building envelope

The building envelope above ground (walls and roof) is planned to be insulated with prefabricated modular panels. Basement walls are planned to be insulated with an external thermal insulation composite system. Prefabricated modular panels consist of a timber frame structure filled with mineral wool (Fig. 2). In principle, also other lightweight structures and insulation materials are conceivable. To get accurate information about the unevenness and roughness of the existing surfaces, 3D laser scanning of the envelope was conducted before the design.

The total thickness of designed modular wall elements is 340-380mm, depending on the surface flatness of the existing wall (Fig. 2 A). The total thickness of the thermal insulation in wall panels is 305-345mm: 30mm wind barrier, 70+195mm insulation between timber frames and 10-50mm light elastic mineral wool to fill the unevenness and roughness of the existing surfaces, U_{wall}=0.11W/(m^2·K). In the wall panel with dimensions ≈2.7×9m, installed in horizontal direction, are up to three preinstalled windows. To minimize joints between the modules and connections of pipes on site, the panels with ventilation ducts (Fig. 2 B) will be installed in vertical direction. According to the structural design of the pilot building, there is no need for additional foundation for the wall module panels. Self-supporting modules will be hanged with the help of designed fixings, allowing adjustment of modules in all directions.

Designed roof elements will be installed on the specially built timber frame (Fig. 2 C) because the original roof has an inward slope and parapet. Therefore, under the formed slope roof, in 0.6-1,2m high attic between old and new roof technical appliances are planned to be placed (e.g. heat exchangers, duct dispensers, automatics etc.). The total thickness of the thermal insulation in the roof modules is 340mm, U_{roof}=0.10W/(m^2·K).

To avoid thermal bridges and to minimize the impact of air leakage and convection, smart connectors and innovative fixings, adhesive sealants and elastic polyurethane (PUR) foam will be used in the joints between the modules. All vertical joints between wall modules will be protected with sealing and steel strips under the facade boards. Horizontal joints will be equipped with slits (drip molds) to prevent rain penetration to the insulation. All internal intersections between modules will be sealed and filled with expansive PUR foam. To avoid having to tighten the existing envelope, it is planned to ensure the airtightness of the building with prefabricated highly-insulated modules. Fig. 2 shows the cross-sections of the designed wall and roof modules (see Fig. 1 left, for locations of structural points).

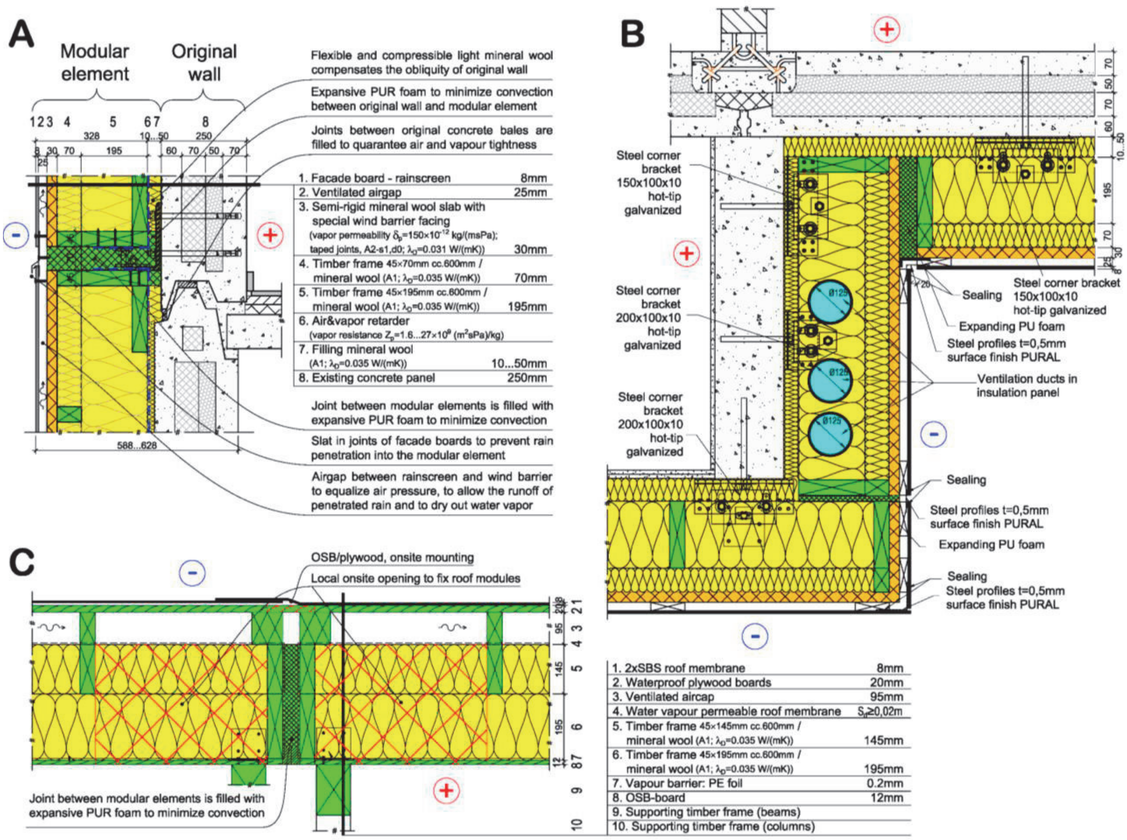

Fig. 2. Designed solutions at the different structural points of the pilot building.

5. Hygrothermal performance of prefabricated wall panels

Longer constructional moisture dry-out periods and obstacles to its capability weaken the hygrothermal condition of the whole building envelope. Therefore, it is necessary to pay special attention to the hygrothermal performance and moisture safety of the design and building processes of highly-insulated buildings. It was previously shown [21] that in highly-insulated buildings, high thermal resistance and vapor permeability of the wind barrier layer are the key components of a well-functioning building envelope and a longer constructional moisture dry-out period is detrimental to the hygrothermal condition. In the common timber-frame wall the PE-foil, as the air and vapor barrier, does not cause any serious problems to the hygrothermal performance [22,23]. In highly-insulated modular panels, installed onto the existing concrete wall, it prevents the moisture dry-out and could pose a higher risk of mold growth.

One of the most critical design tasks was the selection of a vapor barrier for the wall module [24]. The most influential parameters here are a built-in moisture dry-out after the installation of the insulation modules (requires a relatively permeable vapor barrier) and the long-term performance where a vapor tightening barrier is required because the joints of the original wall would not be air- and vapor tight. We did not find any previous studies about this matter from our literature review.

It was confirmed by former studies that a concrete building envelope is affected by weather conditions (temperature, relative humidity, wind driven rain (WDR), radiation, orientation) in such substantial amounts that they cannot be ignored in the further design process of renovation with modular panels. Cracks and openings in the walls contribute to the uncontrolled moisture flux into the structure. With hygrothermal analysis it was found that in our region the south-west oriented wall has about 20% higher moisture content than other sides of the building envelope and with the consideration of impact of WDR, the wall has almost 50% higher moisture content. Analysis showed that the moisture content in the whole external concrete slab is about w=110kg/m^3 in the most critical periods, at the last quarter and the first months of the year [25].

Required hygrothermal performance of studied solutions was ascertained with a smart vapor retarder with changing vapor tightness 0.2m<S_d<5m when the initial moisture content of existing concrete large panel was w≤110kg/m^3 or with 22mm OSB as vapor control layer when the initial moisture content of the existing concrete large panel was w≤75kg/m^3 or with PE-foil as air and vapor barrier when the initial moisture content of the existing concrete large panel was w≤55kg/m^3. For future research, we plan to investigate the hygrothermal performance of insulation panels and connections by field measurements after the whole renovation process of the pilot in autumn 2017.

6. Conclusions

A pilot nZEB renovation of a typical concrete large panel apartment building is planned to be conducted in Estonia. This is one of the first deep energy renovations that has been designed to correspond to the nZEB target of new buildings. In addition to the use of prefabricated modular panels for building envelope insulation, the design solution includes many other tasks to be researched: parallel comparison of two different ventilation solutions: apartment based balanced VHR and centralized balanced VHR; parallel comparison of heating of DHW by solar collectors and sewage heat recovery.

The hygrothermal performance of the building envelope, constructed of concrete large panels and covered with prefabricated modular elements was analyzed in this research. Thermal transmittance of the developed prefabricated modular panels is U≈0.10W/(m^2·K). One of the most critical design tasks was the selection of a vapor barrier for the module panel to avoid problems related with dry-out of possible constructional moisture. A smart vapor retarder with changing vapor permeability was needed.

The analysis and the whole process of design itself showed that it is essential to consider the initial state of the building when highly-insulated module panels are intended to be used for a nZEB renovation. One of the challenges in this process is the decisive importance of the interaction between the design process and the construction work at the building site. Engineers and designers should include hygrothermal modelling into design practices to assure the moisture safety of structures and sustainability in the long term. The analysis, design and other preparation activities of the integrated nZEB design process gave us a unique experience, showing weak links in the chain and helping to prevent major faults in the construction of the pilot and in the further processes of design.

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ORIGINAL ARTICLE

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Commissioning of moisture safety of nZEB renovation with prefabricated timber frame insulation wall elements

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ABSTRACT
An improvement in energy performance for existing buildings is needed to fulfil EU energy policy. The efficient way to accomplish the idea of nearly-zero energy buildings (nZEB) is to apply the integrated design process and application of prefabricated insulation elements paired with the expertise of hygrothermal performance. In the current study, the commission of design and construction with emphasis on moisture safety, relying on known quality control programmes, was applied to assure the compliance of nZEB renovation results of an apartment building, where prefabricated timber frame insulation elements were used. The results confirming that the mould index is below critical level $M < 1$ and moisture content, drying out from the concrete envelope within first 6 months post installation of elements, was 23 kg/m^3 and after that, during the next 12 months 12 kg/m^3. Analysis showed that it is necessary to force contractors and developers to put into practice quality assurance and moisture safety commissioning processes as a mandatory part of contracting. The results have shown that thorough inspection, strict rules of moisture safety and analysis of designed solutions before, during and after renovation are essential and worthwhile for high-quality, sustainable outcomes of nZEB renovation with timber frame insulation elements.

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Moisture safety; hygrothermal performance of buildings; nZEB deep renovation; prefabricated timber frame insulation elements; quality commission

1. Introduction

Prefabrication of buildings has been one method to increase the quality and effectiveness of construction for many decades. Use of prefabricated concrete large-panel (PCLP) construction technology for apartment buildings has been applied in many European countries since the 1960s (Hall and Vidén 2005, Lahdensivu 2012, Barański and Berkowski 2015). In Estonia, the first PCLP building was erected in 1961, when production technology was imported from France. As more than 70% of residential buildings in Europe are over 30 years old and about 35% are more than 50 years old (Balaras *et al*. 2005), a complete technical improvement of their condition has been receiving more attention.

Increasing energy performance has been the driving force for the renovation of old apartment buildings because energy-related measures help to increase cost-effectiveness and the upkeep of buildings (Jurelionis and Šeduikyte 2010, Matic *et al*. 2015). An innovative way of renovation is the application of prefabricated renovation elements which has the potential to reduce costs and renovation time, to lower disturbance for occupants and, at the same time, enhance quality and performance in terms of energy efficiency and indoor climate (Ott *et al*. 2013, Veld 2015, Malacarne *et al*. 2016, Mjörnell 2016, 2011, Ruud *et al*. 2016, Sandberg *et al*. 2016).

In addition to energy performance, it is necessary to pay special attention to the moisture safety measures in the design and building processes of highly-insulated buildings. High thermal resistance and vapour permeability of the external layers are key components of a well-functioning building envelope (Pihelo and Kalamees 2016). Therefore, quality control and commissioning procedures become more and more important when designing, constructing new, and renovating existing energy-efficient buildings. In Sweden, industry standard (ByggaF 2013) is developed to minimise moisture-related problems that incur negative consequences on health, costs for rebuilding and lost confidence in the building industry (Mjörnell *et al*. 2011). Moisture safety methods also exist in other Nordic countries (Geving 2017 Kosteudenhallinta.fi n.d. Sisäilmayhdistys ry n.d.).

Based on European Construction Products Regulation (CPR EU 305/2011), the manufacturers must draw up technical documentation describing all the relevant elements related to the required system of assessment and verification of constancy of performance. European Technical Approval Guidelines (ETAG 023 2006, ETAG 007 2013) can be used for assessments of construction products in line with the requirements. The renovation of buildings is not such a standardised process that one building component is suitable for many buildings because of differences in building typology and climatic conditions. A quality assurance system for the retrofitting process was developed (SQUARE 2008), to ensure that the most efficient measures are chosen and a high level of integrated energy and indoor environmental performance is maintained throughout operation of the buildings.

We see that several single quality assurance and control systems with multiform scope exist. Nevertheless, an inte-

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grated system for nZEB renovation with prefabricated insulation elements does not yet exist. The current study combines the most relevant parts from existing moisture safety and quality assurance systems and tests them in the process of nZEB energy renovation of an apartment building with prefabricated timber frame insulation elements.

2. Methods

2.1. Commission of moisture safety in the construction process

Applicable parts from existing quality assurance systems (SQUARE 2008, ByggaF 2013), and requirements from local legislation and standards were implemented to describe the roles of partakers and assess moisture safety.

- Persons involved in moisture safety process in the current project:
  - Planners and designers: a design company, offering all design parts (was chosen by the client from three candidates by using the best value method);
  - Contractor: a prime contracting and project management company (was chosen by the client from two candidates by using the best value method);
  - Supplier: a producer of custom-made prefabricated timber frame houses (was chosen by contractor);
  - Moisture safety officer for planning: chief structural design engineer from a company who designed the renovation;
  - Moisture safety officer for production: project manager of the contractor, owner's surveyor and executive civil engineer from the supplier;
- Requirements for moisture safety for design were set in the design task and for construction in the design documentation;
- Moisture safety plan was described in design documentation at a general level;
- Moisture inspection was conducted during production and construction processes.

2.2. The case study building

A 5-story PCLP apartment building (series 111–121) with total area 4318 m^2, constructed in 1986 (see Figure 1, left) was renovated by using prefabricated timber frame insulation elements (Pihelo *et al.* 2017). Because of serious thermal bridges in these type of buildings (Ilomets *et al.* 2016), mould growth was present on interior surfaces, especially in the corners of exterior walls and roof. The energy need for heating and domestic hot water was close to 300 kWh/(m^2·a). The building had insufficient ventilation, was subject to overheating during winter and provided unsatisfactory thermal comfort.

The building was renovated to nZEB (see Figure 1, middle and right) in 2017 by using prefabricated timber frame insulation elements filled with mineral wool with density 22 kg/m^3. The thermal transmittance of the external envelope was U = 0.9-1.1 W/(m^2·K) before renovation and was designed to be U = 0.10-0.12 W/(m^2·K) after renovation. See designed wall type 1 and wall type 2 in Figure 2. Wall type 1 was designed for existing PCLP walls. Wall type 2, with gypsum board on room side, was used to close existing open balconies. Mineral wool buffering layer was used in wall type 1 to fill up the gap between the existing uneven structure and the new timber frame insulation element. Buffering layer was fixed in zigzag shape with strings which were released after the element was installed. This layer (and all other layers of insulation, see Figure 2, pos.2 and pos.4–6) was installed in the factory and protected with a plastic foil against weather conditions during transport and on building site.

Designed roof elements were installed on a specially built wooden frame because the original roof had an inward slope and parapet. Therefore, under the formed sloped roof, in a 0.6-1.2 m high attic space between the old and new roof, technical appliances were placed (e.g. heat exchangers, duct dispensers, automatics, etc.).

2.3. Measurements

The hygrothermal performance was measured at one-hour intervals before, during and after the renovation at different points of the external envelope with temperature and relative humidity sensors (Rotronic HygroClip SC05: ∅5 × 51 mm, measurement range: −40° … +100°C and 0 … 100%, accuracy ± 0.3°C and ± 2%). Air and surface temperatures were measured with HOBO temperature/relative humidity/2 external channel (TMC6-HD) data loggers (U12-013, measurement range −20° … + 70°C, accuracy ± 0.35°C). See measurement points in Figure 2.

Figure 1. Overview of the building in 2015 before (left), in summer 2017 during (middle), and in autumn 2017 after (right) the nZEB renovation with prefabricated timber frame insulation elements.

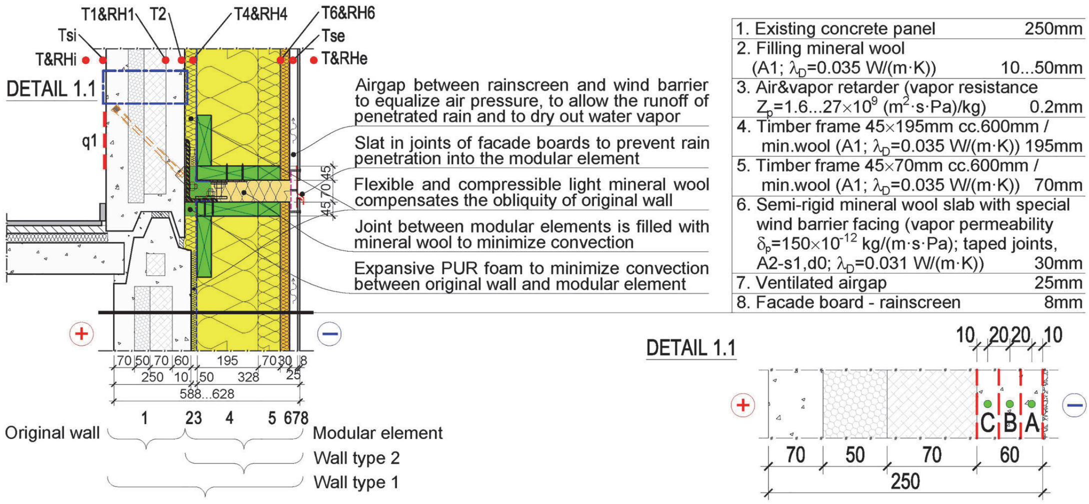

Figure 2. Prefabricated timber frame insulation elements on the PCLP wall.

During construction works, test samples from different parts of the PCLP walls were drilled out and taken to the lab for testing. According to ISO 1920-5:2004, samples were weighed promptly and measured, then dried (dehydrated) in the oven at the lab. Using the mass difference, the moisture content of the material was consequently calculated.

2.4. Simulations

Hygrothermal simulations with software Delphin (Grunewald 1997, Nicolai 2008) were conducted to analyse the performance and to control the quality of the external walls. The model was calibrated with hourly measurement data from the case study building envelope. The influence of moisture dry-out on hygrothermal performance of insulation elements was simulated during design with initial presumptions. After the construction, the simulation was compared with measurements to see the accuracy of initial simulations. For the assessment of moisture safety, hourly measured data of the hygrothermal characteristics was applied for outdoor and indoor climate (see Figure 4, bottom) Table 1.

To study the possible growth rate of mould in structures, the Finnish mould growth model (Hukka and Viitanen 1999, Ojanen *et al*. 2010) was applied. The critical level of mould index (M) was set to $M = 1$ in the current research. This level is described as a very small amount of mould on surface (detectable with microscope) where initial stages of local growth are possible in a very low range.

3 Results

3.1. Design process

Requirements for moisture safety were described in the design task as follows:

Table 1. Properties of materials used in simulations.

Material RRH	Thermal conductivity λ, W/(m·K)	Moisture storage function w, kg/m^3 33%	55%	75%	83%	97%	Water vapour resistance factor μ, - 83%	Density ρ, kg/m^3	Open porosity m^3/m^3	Water absorption coefficient A_w, kg/(m^2·s$^{0.5}$)
Concrete* A	1.500	38.0	53.0	78.0	86.0	134	41.0	2320	0.14	0.0200
Wood chip insulation* A	0.140	6.00	11.0	15.0	21.0	32.0	3.80	500	0.93	0.0089
Phenolic foam insulation* A	0.064	0.25	0.32	0.36	0.54	0.98	2.85	30	0.90	0.0010
Timber (pine) A	0.130	32.0	45.0	80.0	108	185	40.0	450	0.62	0.0155
Mineral wool wind barrier B	0.031	0.21	0.28	0.29	0.96	3.30	1.50	104	0.90	
Mineral wool insulation B	0.035	0.14	0.18	0.36	0.80	2.40	1.20	22	0.98	
Vapour retarder (0.2m < S_d<5 m) B	0.230						800	460	0.59	0.0001

Notes: Material properties are based on simulation software Delphin database with adjustments, see remarks:
* Materials in the original PCLP wall.
A Material properties adjusted with lab tests and literature data.
B Material properties adjusted with data from material producer.

- The building envelope must be designed and constructed in such a way as to ensure moisture safety of the building;
- The hygrothermal performance of building envelope is covered by standards EN 15026:2007 and EN ISO 13788:2012;
- Dampness, mould damages and degradation of materials should be avoided;
- Design must ensure that material-based critical humidity is not exceeded (i.e. humidity of the material, exceeding which may cause moisture damages including deterioration of surface, microbial growth or degradation of material);
- The critical humidity depends on the material and is determined by the manufacturer's data. In the absence of the manufacturer's data, relative humidity of 75% and a corresponding moisture content of the material are used as critical moisture limit values.

Design requirements for moisture safety were sufficient in general and were implemented to project documentation where appropriate. The only problem was with the determination of the vapour permeability of the air barrier. The designer's first choice (plastic vapour barrier as a typical solution for timber frame exterior walls) was acceptable according to EN ISO 13788 methodology. Nevertheless, PE-foil air and vapour barrier turned out to be too vapour tight to allow dry-out of constructional moisture from the existing PCLP wall and could have caused mould growth in mineral wool and timber parts. Dynamic hygrothermal simulation (according to EN 15026) was unknown for the designer. The developer's moisture experts conducted required simulations (Pihelo *et al*. 2016a, 2016b) and determined requirements for moisture content of the old PCLP wall (as part of the wall type 1) before installation of elements ($w \leq 110$ kg/m^3) and water vapour permeability of air and vapour barrier (0.2m@RH85% <S_d<5m@RH20%). PE-foil as air and vapour barrier was used with no problems on wall type 2, i.e. where insulation elements were directly connected to indoor conditions (old balconies that became a part of indoor premises).

3.2. Construction process

Requirements for moisture safety in the construction process were described in design documentation:

- Special attention has to be paid to the protection of products against moisture;
- The surfaces to be covered must be dry and free of water, ice or snow;
- The order of work and weather protection should be planned in a way ensuring that rainwater does not get into the structures;
- In case of interruption of works, temporary weather protection (e.g. tarpaulins) must be used in a way which prevents the wetting of the insulation due to rain and flooding water;
- The wood materials supplied to the construction site must be protected from the weather;
- The moisture content of installed wood should stay below 15% (16–1% of measurement accuracy);
- Wooden structures must be separated from concrete structures by a damp- and waterproofing material layer.

Several moisture safety setbacks were recorded during the construction process. The contractor slipped up on many aspects of the designed requirements. Because of the delays in work schedule due to the slower mounting of the installation brackets and the first insulation elements, the contractor did not always respect the required weather protection criteria.

Designed roof elements were planned to overhang the facade, and it was planned to use cranes to lift the elements. Therefore, it was not possible to install roof elements before the wall elements, leading to the sides of wall elements remaining open and vulnerable to rain for some time. After pointing out some critical mistakes, rain-protecting tarpaulins were used during the prefabricated elements installation works. Leakages found were dried out mechanically before the final closure of the structures with elements.

Even if the preliminary facade protection was used during rainy days, some parts of facade were still affected by wind-driven rain (see darker area between window openings in Figure 3, top). In the worst-case, rainwater flowed inside the element or between the element and old wall (see Figure 3, bottom).

3.3. Hygrothermal performance

Figure 4 (top) shows the comparison of long term hygrothermal measurements and simulations of the timber frame insulation elements in points between the timber frame element and the mineral wool buffer layer (point 4) and between the rigid mineral wool and the timber frame element (point 6). Figure 4 (bottom) shows climate data, measured at the case study building and water vapour volume v (g/m^3) measured in points 4 and 6.

Long term hygrothermal measurements of the timber frame insulation elements (see Figure 2 for measurement points) showed that drying out of moisture from insulation element (see Figure 4) and from PCLP (see Figure 6) was in agreement with expected rates.

Results of calculations with the mould growth model showed that critical RH was exceeded for a short-term (see Figure 5, left) and therefore, the mould index was under critical level ($M < 1$) in measured points (see Figure 5, right).

Moisture content measurements of PCLP walls during the construction and simulations at different depths of the concrete envelope assured that moisture content is below limit criteria (see Table 2 and Figure 6).

In Figure 6 are shown general intervals from the installation of elements up to start of use of building along with consecutive calculated moisture content (MC) at different depths of PCLP, marked in Figure 2, detail 1.1 as points A, B and C.

On average moisture content trends (see Figure 6, bar chart), moisture content values in every 6 months are shown. Critical moisture content in the PCLP ($w = 110$ kg/m^3) was never exceeded during the installation of timber

Figure 3. Installation of prefabricated facade insulation elements with insufficient moisture protection (top). Rainwater has flowed inside the element and between the element and the old wall (bottom).

frame elements or after the start of use of the building. The overall moisture content that dried out from the concrete wall, starting from installation in May 2017 to the end of the year 2018, was about 35 kg/m^3. The quantity of dried out moisture during the first 6 months was 23 kg/m^3 (i.e. 1.4 kg/m^2 of 60 mm concrete panel) and during the next 12 months it was 12 kg/m^3 (0.7 kg/m^2 of 60 mm concrete panel).

4 Discussion

Described hereinbefore, the results of measured and calculated values of temperatures and relative humidity in the analysed points are showing a good correspondence with our expectations (Pihelo *et al*. 2016a, 2016b) and are in accordance with defined boundaries formed at the preliminary analysis and design phase of moisture safety and performance quality commission process.

Though existing methods of commission (Kosteudenhallinta.fi n.d., SQUARE 2008, ByggaF 2013) are very good, some updates taking into account local practice may be necessary. We see that several developing steps must be taken by authorities locally, both in legislation and standardisation practices, to keep up with the changing demands and behaviour of tenants and owners of nZEB. It is also necessary to force contractors and developers to put quality assurance and moisture safety commissioning processes into practice as a mandatory part of contracting. This has been pointed out by other authors as well (Mjörnell *et al*. 2011, Jankovic 2019) and it may serve as a useful tool against major faults and possible claims of damages.

Relative humidity (*RH*) and moisture content (*w*) measurements of the structures, also calculations of the mould index (*M*) have given results confirming that critical moisture levels were not exceeded. Well prepared hygrothermal analysis and the implementation of design solutions during the installation work process will serve as prerequisites to a successful outcome. We agree with other authors (Vinha 2007, Geving 2017, Colinart *et al*. 2019) that it is highly important to consider the weather conditions, and moisture safety rules on site must be strictly followed to reach such results. Outside of critical levels, moisture problems will occur, weakening strength properties of materials. A rise of the volume of spores and bacteria of fungi in the indoor air and on surfaces will be harmful for human health. High moisture content induces mould formation and degradation of structures which may lead to a very complicated and expensive

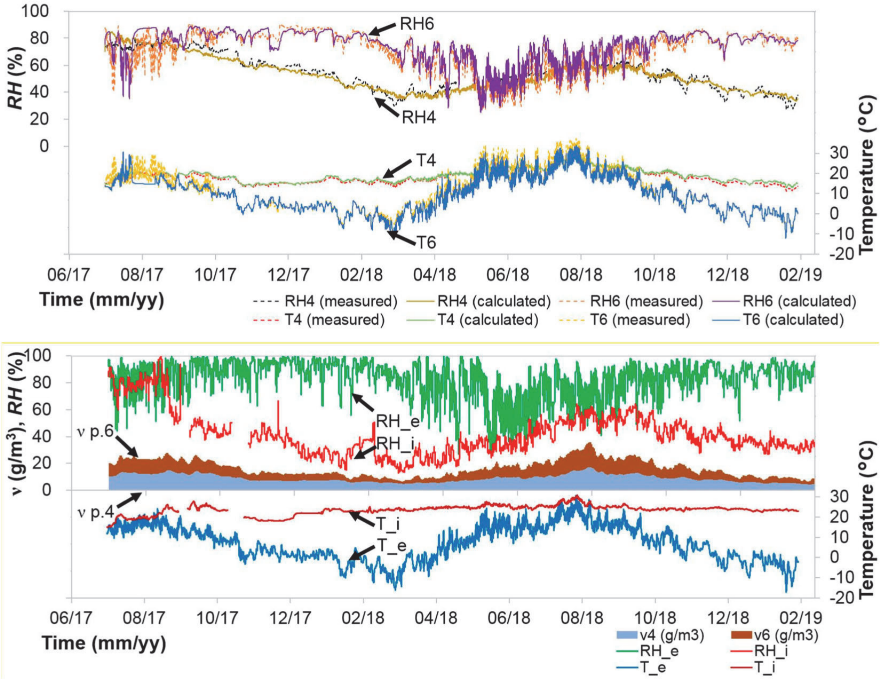

Figure 4. Temperature (*T*) and relative humidity (*RH*) inside the timber frame insulation element (top). Indoor and outdoor temperatures (T_i, T_e), *RH* (RH_i, RH_e) and water vapour volume (v) measured at the case study building (bottom). See Figure 2 for measurement points.

Table 2. Moisture content measurements of samples of PCLP during construction, before installation of prefabricated wall elements (May–June 2017).

Sample No. *	1–12	3–22	4–42	5–42	1–41	3–31	4–11	5–11
Diameter d, mm	43.5	43.3	43.4	43.3	94.2	94.5	93.9	94.1
Moisture content *w*, kg/m^3	43.3	62.7	63.1	54.9	53.9	76.7	53.6	60.7
Moisture content *u*, vol.%	4.3	6.3	6.3	5.5	5.4	7.7	5.4	6.1

Note: * Sample No. describes the floor (1–, 3–, etc) and relative placement of the PCLP element on the wall (–12, –22, etc).

reconstruction of the whole building envelope. This is also well studied in other countries, leading to the same critical points (Fedorik *et al*. 2015, Gullbrekken *et al*. 2015).

We see that design which does not consider a number of important physical phenomena, including the variation of material properties with moisture content and weather dissimilarities, underestimates the real state of buildings. Based on an example of concrete wall measurements in the current project, it was confirmed that short-term superficial observation of moisture content on the surface area of

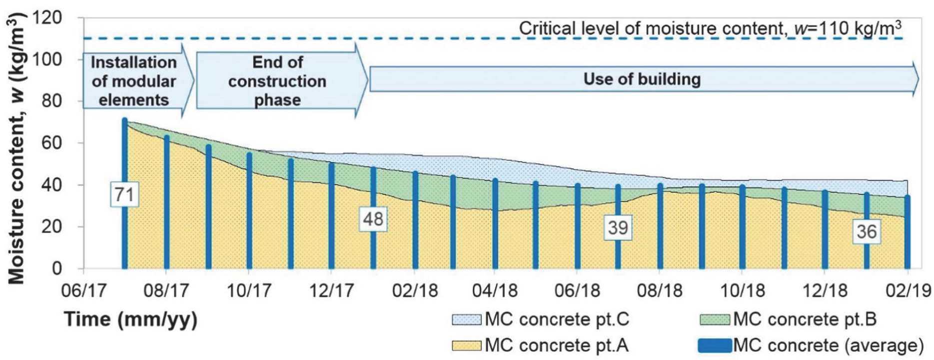

Figure 6. Calculations of moisture content (MC) of PCLP with calibrated simulation model (see measurement points in Figure 2, detail 1.1).

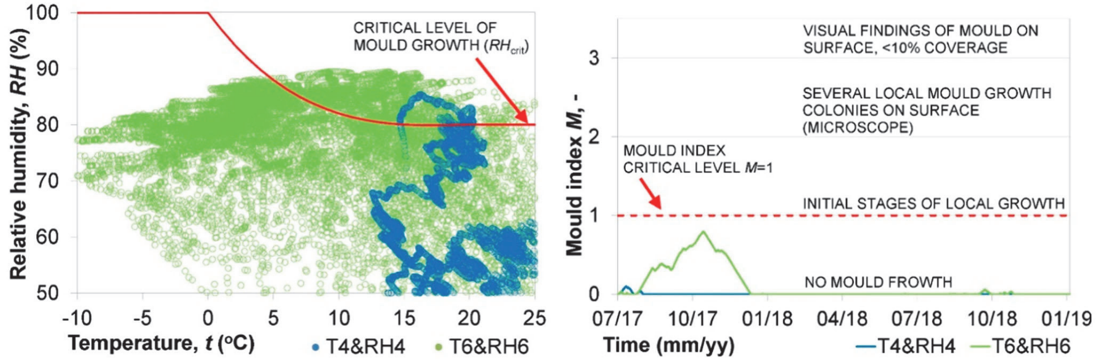

Figure 5. Temperature (T) and relative humidity (RH) in critical points compared to critical level of mould growth (left). Calculated mould index M in critical points (right). See Figure 2 for measurement points.

material does not reflect the precise amount of moisture in the structure studied. Because of redistribution phenomenon, at a depth of 50 mm the volume of moisture may reach a level as much as two times higher than at the surface and its dry-out period may be almost a year to reach the surface moisture content. So, use of proper weather protection kit with proper moisture-proof sealants, both for delivered materials and structures, must be included as a mandatory tool. The water repellent could be another useful solution (especially for high buildings) that minimises moisture adsorption and allows excess moisture dry-out. Also, monitoring of weather forecasts (for possible precipitation) at the work site is a good way to avoid mistakes such as those described above.

The study showed that the common knowledge of civil engineer might be insufficient to solve more complicated building physics tasks. To guarantee a good moisture safety management in the design and construction process a responsible specialist on moisture safety would be necessary. For larger countries special occupational qualification standards are appropriate. For smaller countries where more universal engineers are required, the demand can be solved by continuing education. Even the Building Act requires moisture safety (a construction work may not present a threat to the health). Also, more detailed guidelines are needed about the implementation of these requirements. The Swedish moisture safety standard (ByggaF 2013) is a good example here.

Despite some setbacks from the contractor side at the beginning of the current project, good results for moisture protection were attained with the help of co-operation between the developer, contractor and experts. It was proved that monitoring of moisture safety and quality commission are unavoidable steps in nZEB and deep energy renovations. One of our suggestions, after lessons learnt during the current research, is to execute a certification system of building physics specialists – professional moisture safety experts who will manage the moisture safety programme and guarantee that it is strictly followed in nZEB contracting.

5 Conclusions

Within this research, a quality commission of moisture safety of nZEB renovation of a multi-story house with prefabricated timber frame insulation elements was performed. With preliminary analysis and continual surveillance, we claim that it is possible to attain good results and build sustainable solutions according to the up-to-date requirements of nZEB renovation in a cold and humid climate. The prerequisites for good hygrothermal performance and design are preliminary measurements of the building state, carefully considered vapour control and airtight layer on the concrete envelope, the vapour permeability of which is controlled by hygrothermal calculations, and insulation and wind barrier layers with high thermal resistance and vapour permeability. It was calculated that in critical points, mould index $M < 1$ and critical moisture content of PCLP ($w = 110\ kg/m^3$) was never exceeded. Drying out of the concrete envelope moisture content within the first 6 months post installation of elements was 23 kg/m^3 and after that, during the next 12 months, it was only 12 kg/m^3.

Above all, strict rules and follow-up of moisture safety at the work site and highly motivated and skilled employees with effective management are of the utmost importance. There is a high need for the implementation of a local professional certification system of moisture safety specialists. The confident results of current research are giving a strong signal to institutions, real estate developers, engineers, and designers, and inspire them to extend their design practices and improve quality assurance processes.

Disclosure statement

No potential conflict of interest was reported by the authors.

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PUBLICATION VI

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Article

Development and Performance Assessment of Prefabricated Insulation Elements for Deep Energy Renovation of Apartment Buildings

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Abstract: A need for the refurbishment and renewal of the existing building stock has been in focus for many decades, principally because of excessive global energy consumption and pollution. This paper presents a methodology and the results of analysis of choices of realizable sets of timber frame prefabricated insulation elements for major renovation of apartment buildings. Numerous combinations of elements with different characteristics were analyzed by applying measurements, interviews, and building performance simulation software, and thereupon their performance, installation eligibility, and concurrent cost levels were compared. Mineral wool board with a special wind barrier facing was found to be the best material as a wind barrier from the perspective of hygrothermal performance. An air and vapor barrier should have sufficient vapor permeability to allow dry-out of constructional moisture. It is possible to renovate apartment buildings to meet the nZEB energy performance requirements and their moisture safety can be guaranteed without paying high relative difference cost. Calculations showed that the global cost was lower for solutions with some mold growth risk. Great care is needed when decreasing costs without simultaneous hygrothermal analyses. The facade cladding was found to have the highest influence on the initial cost of the prefabricated insulation element.

Keywords: hygrothermal performance of buildings; nZEB renovation; deep energy renovation; moisture safety; prefabricated timber frame insulation elements; quality assessment

1. Introduction

If the building materials and structural elements are nearing the end of their service life and the energy performance of the building needs to be improved, the owner of the building has to take measures required to ensure that the relevant criteria are met. As in Europe, more than 70% of the residential buildings are over 30 years old and about 35% are more than 50 years old, complete technical improvement of their condition has been receiving increasing attention [1,2]. Energy performance of building directive (EPBD) [3] requires all new buildings to be nearly Zero Energy Buildings (nZEB) as of the year 2020 and to renovate almost all buildings by the year 2050. Due to the reduction of energy use during the lifetime of buildings, renovation resulted in a reduction of global warming potential [4]. Case studies have shown the viability of the nZEB renovation measures to improve the condition of residential building stock in Croatia [5], Spain [6,7], Poland [8], and the Mediterranean climate [9]. The outcomes show huge potential energy and economic savings and support deep energy renovation needs [10,11].

In the cold climate, additional thermal insulation is always needed to radically improve the energy performance of buildings. To fulfill future nZEB requirements, the building envelope should be more highly insulated than buildings designed some years ago [12]. A highly insulated building envelope is an inevitable prerequisite for nZEB renovation in all climates. López-Ochoa [13] analyzed the energy, environmental, and economic impacts of the energy renovation of thermal envelopes and optimized the insulation thickness to be added to the walls, roofs, and first floor.

A highly insulated building envelope requires thoroughgoing hygrothermal analysis to avoid moisture damage [14,15]. Therefore, in the design of nZEB renovation, hygrothermal performance of the building envelope and sustainability should also be analyzed [16] and considered as an important selection criteria. On the other hand, too many selection criteria makes analysis difficult [17] for practitioners and consultants. Qi [18] showed that quality control during the renovation preparation stage is critical to ensure that quality failures are reduced in numbers and severity. In the changing climate conditions, it means that the market participants must find efficient ways to improve the quality of design and installation to meet increasing requirements of energy and hygrothermal performance of new and existing buildings.

La Fleur et al. [19] showed that the cost of the demolition and construction of a new building is higher compared to energy renovation to the same energy performance. This makes renovation the first choice, when there exists need for residences in that region. The cost of renovation is an important criteria for decision making and determining renovation solutions. Gustafsson [20] analyzed energy renovation measures in Sweden and showed that all renovation measures resulted in an increased life cycle cost (LCC), compared to the reference building. Firląg et al. [8] analyzed nZEB solutions for heating dominated climate and showed that nZEB renovation is not yet cost optimal in Poland. Patiño-Cambeiro et al. [7] analyzed nZEB renovation solutions for Spanish building stock and showed that more active financial support, together with the dissemination of the technical requirements and the benefits obtained from energy renovations are needed. Hu [21] indicated that in the optimum scenario, investing in energy-efficient retrofitting and renewable energy, when combined, produced close to a 90% reduction in the life cycle cost compared to the pre-renovation state. Kuusk [22] showed that for a concrete large panel apartment building in Estonia, additional insulation of 200–300 mm to the external wall leads to the greatest reduction in the global cost and primary energy use and that to reach the nZEB level, thermal transmittance of the external wall should be $U \leq 0.15$ W/(m^2·K) [23]. Hirvonen et al. [24] showed that improving the building envelope is an effective way to reduce emissions of detached houses in Finland.

Fotiou [25] showed that the achievement of ambitious energy-efficiency targets in the long-term heavily depends on pursuing a fast and extensive renovation of existing buildings. External thermal insulation composite systems (ETICS) have been used for decades on masonry, concrete, and other substrates. ETICS primarily fulfill the functions of thermal insulation and protect the building against the influences of weather. Many authors [26–28] have pointed out that as to ETICS, durability issues, including the degradation of the surface and aging of the materials, are the most urgent ones. Installation of timber (or other similar) frames, filled in between with insulation layers and covered by wind and weather protective facade layers, to the external envelope manually on the building site is another common method for energy refurbishment as well as for building extensions. Both methods are based on onsite field work, accompanied by long-lasting manual labor, low efficiency, and use of scaffolding on the external envelope. Because of unpredictable weather conditions and varying quality of installation the results obtained are not always in agreement with expectations [29]. Therefore, the building owners, construction companies, and other market participants are in search of alternatives to improve the quality of the existing building stock by means of prefabrication and by lesser disturbance to a building's occupants.

An innovative method of renovation is the application of prefabricated renovation elements, which has the potential to reduce costs and renovation time, lower disturbance for inhabitants, and enhance quality and performance in terms of energy efficiency and indoor climate [30–32]. The recent research on technical, financial and social barriers and challenges in deep renovation of buildings points out that the main barriers are not related to specific technical problems but are due to insufficient deep renovation and nZEB knowledge, in the case of both building owners (i.e., awareness and commitment) and designers (i.e., managing properly the design and construction process in order to guarantee the expected performance and targets set) [33,34].

The literature review and described hereinbefore projects reveal that many development programs have focused primarily on energy and cost-effectiveness with a commitment to develop state-of-the-art implementation of prefabricated insulation elements for deep energy renovation. However, most of them have not analyzed (or reported the results of) the hygrothermal performance associated with the original building envelope and its condition. The current study combines hygrothermal and energy performance analysis with cost-efficiency calculations to find a suitable solution for nZEB renovation of apartment buildings with prefabricated wall insulation elements.

2. Methods

2.1. Analyzed Building Envelope Construction Types

In total, 1620 dimensional, conditional, and material combinations of prefabricated timber frame insulation elements were analyzed (see Figure 1 and Table 1). The cost (including production, installation, maintenance, and energy use), hygrothermal performance, and handling on installation were evaluated by considering the interaction of various parameters:

- Initial moisture content (IMC) of original concrete facade by volume: w = 85 kg/m^3, 95 kg/m^3, 110 kg/m^3 (i.e., IMC by mass (kg/kg): u = 3.7%, 4.1%, 4.7%);
- Air and vapor barriers (see Figure 1, layer B): vapor barrier with varying water vapor resistance, original wall without vapor barrier layer, polyethylene (PE) foil;
- Timber framing (see Figure 1, layer C): 45 mm × 120 mm, 45 mm × 145 mm, 45 mm × 195 mm;
- Types of insulation in prefabricated timber frame element (see Figure 1, layer C): mineral wool (MW), cellulose wool (CW); thickness of insulation with 50 mm MW buffering layer (see Figure 1, layer A): 170 mm, 195 mm, 245 mm;
- Wind barriers (see Figure 1, layer D): sheathing membrane, gypsum board + sheathing membrane, fiber cement board, wood fiberboard, MW board with special wind barrier facing;
- Ventilated air gap with vertical timber battens (see Figure 1, layer E) 28 mm × 70 mm;
- Facade systems (see Figure 1, layer F): wooden boarding, plastic boarding/siding, metal profile sheets, cement fiberboards, facade stones cladding, plastered facade weatherboard.

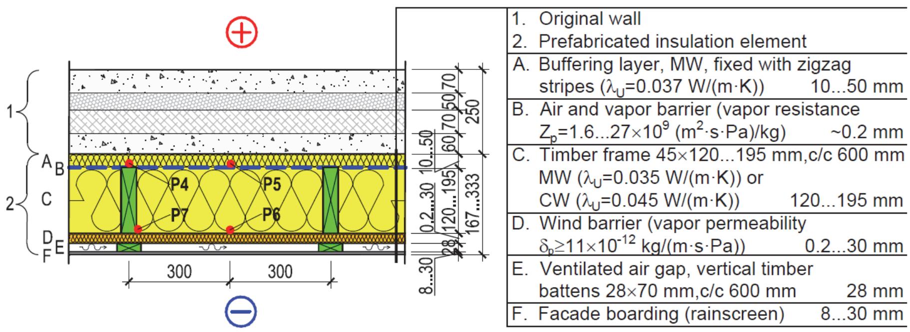


Figure 1. Horizontal cross-section of the original wall with installed prefabricated timber frame insulation element and analyzed critical points.

The materials of the designed and studied structures are described in Figure 1 and in Table 1. Thermal transmittances of the studied structures are shown in Table 2. Analyzed in prefabricated elements layers of materials are marked with letters A to F. Alternatives of the air and vapor barrier layer are marked with B1 to B3. Alternatives of the insulation layer are marked with C1 and C2.

Alternatives of the wind barrier layer are marked with D1 to D5. Alternatives of the facade materials are marked with F1 to F6.

Table 1. Description of materials (see Figure 1) in sets of analyzed structures. *.

Material Layer		Frame Thickness, See Figure 1, Layer C 120 mm	145 mm	195 mm
A	Buffering layer	Mineral wool (MW) 50 mm (thermal conductivity λ_U = 0.037 W(m·K))		
B1	Air and vapor barrier	Product ~0.2 mm (with varying water vapor resistance, depending on *RH*, 0.2 m at *RH* 85% ≤ S_d ≤ 5 m at *RH* 20%)		
B2		Without vapor barrier layer, air tightness is guaranteed by other means		
B3		PE-foil ~0.2 mm (S_d ≥ 50 m)		
C1	Timber frame, insulation type, thickness, thermal conductivity	45 mm × 120 mm MW 120 mm λ_U = 0.035 W/(m·K)	45 mm × 145 mm MW 145 mm λ_U = 0.035 W/(m·K)	45 mm × 195 mm MW 195 mm λ_U = 0.035 W/(m·K)
C2		CW 120 mm λ_U = 0.045 W/(m·K)	CW 145 mm λ_U = 0.045 W/(m·K)	CW 195 mm λ_U = 0.045 W/(m·K)
D1	Wind barrier	Sheathing membrane ~0.2 mm (S_d ≤ 0.015 m at *RH* 85%)		
D2		Gypsum board 9 mm (vapor permeability $\delta_p \geq 25 \times 10^{-12}$ kg/(m·s·Pa), λ_D = 0.19 W/(m·K)) + sheathing membrane (see position D1)		
D3		Fiber cement board 9 mm ($\delta_p \geq 11 \times 10^{-12}$ kg/(m·s·Pa), λ_D = 0.26 W/(m·K))		
D4		Wood fiberboard 22 mm ($\delta_p \geq 40 \times 10^{-12}$ kg/(m·s·Pa), λ_D = 0.050 W/(m·K))		
D5		MW board 30 mm with special wind barrier facing ($\delta_p \geq 110 \times 10^{-12}$ kg/(m·s·Pa), λ_D = 0.031 W/(m·K))		
E	Ventilated air gap	Vertical timber battens 28 mm × 70 mm, c/c 600 mm		
F1	Facade system	Wooden boarding		
F2		Plastic boarding/siding		
F3		Metal profile sheets		
F4		Cement fiberboard		
F5		Facade stones (cladding system)		
F6		Facade weatherboard with plaster		

* Materials' data are from the database of the calculation program Delphin [35,36] and the properties are adjusted with lab tests and/or literature data.

The structure of the prefabricated insulation element is based on timber frames (c/c 600 mm) with different thicknesses (see Figure 1, layer C, 120–195 mm), where air and vapor tightness from the inner side has to be guaranteed with an air and vapor barrier layer (see Figure 1, layer B) or by other means with original wall treatment and from the external side covered with a wind barrier layer (see Figure 1, layer D). The main insulation layer (see Figure 1, layer C) of the element consists of MW with density ρ = 22 kg/m^3 or CW with density ρ = 70 kg/m^3. To minimize convection in between the structures and to compensate the roughness of the original wall, 50 mm MW (ρ = 20 kg/m^3) as the buffer layer was added onto the back side of the prefabricated element (see Figure 1, layer A). The buffering layer is fixed in zigzag with strings, which are released after the element is installed. The buffering layer and all other layers of insulation are installed in the factory and are protected with plastic foil against weather damage during transport and on the building site. In hygrothermal analysis all sets installed are considered to be airtight and the wall elements covered with weatherproof facade boarding, thus not affected by wind-driven rain.

Table 2. Thermal transmittance U_c (W/(m^2·K)) * of analyzed sets with different insulation materials (mineral wool (MW) and cellulose wool (CW)) and wind barrier layers. See Table 1 for description of layers D1–D5.

Wind Barrier Layer	Thermal Transmittance U_c, W/(m^2·K) * (Frame Thickness, Layer C1 or C2)					
	120 mm		145 mm		195 mm	
	MW	CW	MW	CW	MW	CW
D1	0.20	0.22	0.18	0.20	0.15	0.17
D2	0.20	0.22	0.18	0.20	0.15	0.17
D3	0.20	0.22	0.18	0.20	0.15	0.17
D4	0.18	0.20	0.17	0.18	0.14	0.16
D5	0.17	0.18	0.15	0.17	0.13	0.15

* Thermal transmittance is calculated with the existing original wall construction ($R_{exist.wall}$ = 1 m^2·K/W).

2.2. Reference Building

A typical five-story apartment building with a total heated area of 2968 m^2, constructed of prefabricated concrete large panel elements in 1966 (serial project 1–464), was selected for the reference building (see Figure 2). Prefabricated concrete large panel apartment buildings were typical and built in Eastern Europe during the 1960–1990s. For example, 2 million m^2 of prefabricated concrete large panel apartment buildings was built during that period in Estonia and 4.7 million m^2 in Vilnius, Lithuania [37]. This building type needs deep energy renovation because of serious thermal bridges [38], high thermal transmittance of the external walls (U_{wall} = 0.8–1.5 W/(m^2·K)), insufficient performance of ventilation [39], high indoor humidity loads [40], and corrosion damages of concrete facades [41].

Figure 2. Overview of the reference building in 2014 before (**left**) and in 2015 after (**right**) the renovation.

2.3. Hygrothermal Performance of Exterior Wall: Measurements and Simulations

Hygrothermal simulations with the software Delphin [35,36] were conducted to analyze the performance of the external walls on the basis of values of temperature and relative humidity in critical points (see Figure 1, points P4, P5, P6, P7). Delphin is a simulation program for coupled heat, moisture and matter transport in porous building materials and it is used for different applications, e.g., calculation of mold growth risks with consideration of climate impacts, structure conditions and materials modelling. The moisture mass balance is expressed according to Equation (1):

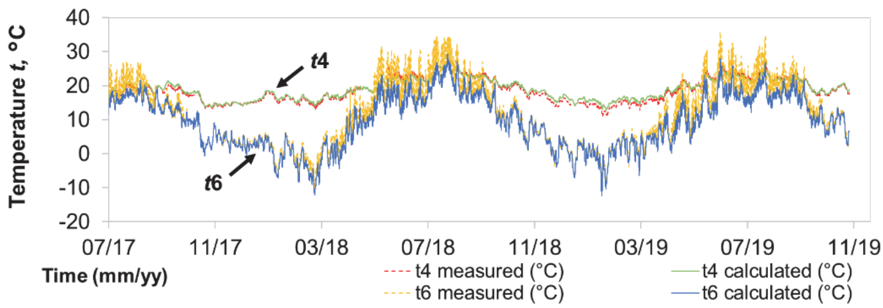
$$\frac{\partial}{\partial t}\rho^{m_{w+v+i}}_{REV} = -\frac{\partial}{\partial x}\left[j^{m_w}_{conv} + j^{m_v}_{conv} + j^{m_v}_{diff}\right] + \sigma^{m_{w+v+i}}_{REV} \quad (1)$$

where $\rho_{REV}^{m_{w+v+i}}$ is moisture density in reference volume (liquid water + vapor + ice) (kg/m^3), $\sigma_{REV}^{m_{w+v+i}}$ is moisture sources/sinks in reference volume (kg/m^3·s), j_{conv} is convective flux (kg/m^2·s), j_{diff} is diffusive flux (kg/m^2·s), m is mass, v is vapor, w is water, and i is ice. The energy balance is expressed according to Equation (2):

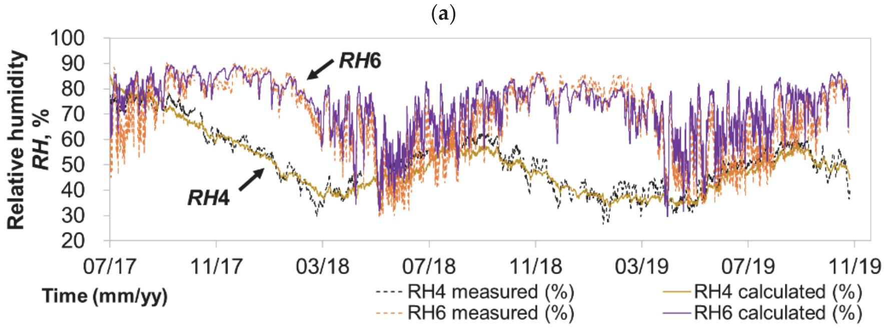
$$\frac{\partial}{\partial t}\rho_{REV}^{U} = -\frac{\partial}{\partial x}\left[j_{diff}^{Q} + u_{l}\cdot j_{conv}^{m_{l}} + u_{g}\cdot j_{conv}^{m_{g}} + h_{v}\cdot j_{diff}^{m_{v}} + h_{voc,g}\cdot j_{diff}^{m_{voc,g}}\right] + \sigma_{REV}^{U} \quad (2)$$

where ρ_{REV}^{U} is the internal energy density in reference volume (J/m^3), σ_{REV}^{U} is energy sources and sinks in reference volume (W/m^3), j_{diff}^{Q} is heat conduction (W/m^2), j_{conv} is convective flux (kg/m^2·s), j_{diff} is diffusive flux (kg/m^2·s), m is mass, g is gas, v is vapor, l is liquid, u is specific internal energy (J/kg), h_v is the specific enthalpy of water vapor (J/kg), $h_{voc,g}$ is the specific enthalpy of gaseous volatile organic compounds (J/kg).

To calibrate the calculation model in Delphin software program, field measurements were conducted in a concrete large panel apartment building renovated in 2017 by using prefabricated timber frame insulation elements [42,43]. Temperature and relative humidity were measured at one-hour intervals before, during and after the renovation at different points of the external envelope with temperature and relative humidity sensors Rotronic HygroClip SC05: ∅ 5 × 51 mm, measurement range –40 to +100 °C and 0–100%, accuracy ±0.3 °C and ±2%. Air and surface temperatures were measured with HOBO TMC6-HD temperature/relative humidity/2 external channel data loggers U12-013: measurement range from –20 to +70 °C, accuracy ±0.35 °C. A good agreement between the measured data and the calculated values was achieved (see Figure 3).



(a)



(b)

Figure 3. Measured and calculated temperature t (**a**) and relative humidity RH (**b**) in the timber frame insulation element, in points 4 and 6. See Figure 1 for the measurement points P4 and P6.

2.4. Assessment of Hygrothermal Performance

To assess the hygrothermal performance of the building envelope, the risk of mold growth as criterion was used. A mathematical model for the calculation of mold growth and decline and the mold index in varying conditions [44,45] was used in this research.

According to this model, under fluctuating humidity conditions, the total exposure time for the response of growth of mold fungi is affected by the time periods of high and low humidity conditions, as well as the humidity and temperature levels. In the simulation of mold growth, it is crucial to know the lowest (threshold) levels at which fungal growth is possible on different materials. The importance of the duration of such conditions is also significant. There are certain minimum and maximum levels for the moisture content of material, water activity or temperature between which fungi can grow in wood. Under these favorable conditions, mold growth may start and continue at different rates. The time period needed for the onset of mold growth and growth intensity are mainly dependent on water activity, temperature, exposure time and surface quality of the substrate [44,45]. The boundary curve for the risk of mold growth in the range of temperature between 5 and 40 °C on a material can be described by a polynomial function, see Equation (3):

$$RH_{\text{crit}} = \begin{cases} -0.00267 \cdot t^3 + 0.16 \cdot t^2 - 3.13 \cdot t + 100 & \text{when } t \le 20\ ^{\circ}\text{C} \\ RH_{\text{min}} & \text{when } t > 20\ ^{\circ}\text{C} \end{cases} \quad (3)$$

where t is temperature (°C) on the investigated material surface and RH_{min} represents the minimum level of relative humidity (%) at which mold growth is possible (varies according to the sensitivity of the material, see Table 3) [45].

Table 3. Mold growth sensitivity classes, some corresponding materials and RH_{min} values [45].

Sensitivity Class	Materials	RH_{min}
Very sensitive	Untreated wood, sapwood	80%
Sensitive	Glued wooden boards, polyurethane (PUR) with paper surface, planed pine and planed spruce	80%
Medium resistant	Concrete, aerated and cellular concrete, glass wool, polyester wool	85%
Resistant	PUR polished surface	85%

The safe value of the mold index (M) was set in the current study at $M < 1$ (no mold growth) and the critical value at $M = 2$ (several local mold growth colonies on surface) according to the mold index model (see Table 4). Therefore, the mold index $1 \le M < 2$ is considered as a low risk of mold growth (small amounts of mold on surface, initial stage of growth) [46]. The mold growth sensitivity class (see Table 4) 'sensitive' for the used timber, timber-based materials and gypsum board with paper in the installed prefabricated insulation elements and in the existing envelope was assigned for calculations. For the other materials, the class 'medium resistant' was set.

Table 4. Description of mold indexes [45].

Mold Index (M)	Description of Mold Growth
0	No growth
1	Small amounts of mold on surface (microscope), initial stage of local growth
2	Several local mold growth colonies on surface (microscope)
3	<10% coverage, or <50% coverage of mold (microscope)
4	10–50% coverage, or >50% coverage of mold (microscope)
5	Plenty of growth on surface, >50% coverage (visual)
6	Heavy and tight growth, coverage about 100%

2.5. Climate Conditions

According to the Köppen-Geiger climate classification [47], Estonia belongs to cold (continental) humid climate with warm summers (DfB). In the assessment of hygrothermal risks, the hourly data of the moisture reference year (MRY), critical to mold growth and water vapor condensation in Estonia, was applied to outdoor climate [48]. Indoor climate measurements from Estonian dwellings [49,50] were used to determine critical indoor hygrothermal conditions. For simulations, the following conditions were used: average indoor temperature, which is dependent on the outdoor temperature and indoor humidity class 3 (moisture excess $2 \leq \Delta v \leq 6$ g/m^3 depending on outdoor temperature), representing dwellings with a high humidity load and high occupancy according to the national annex of standard [51], see Figure 4.

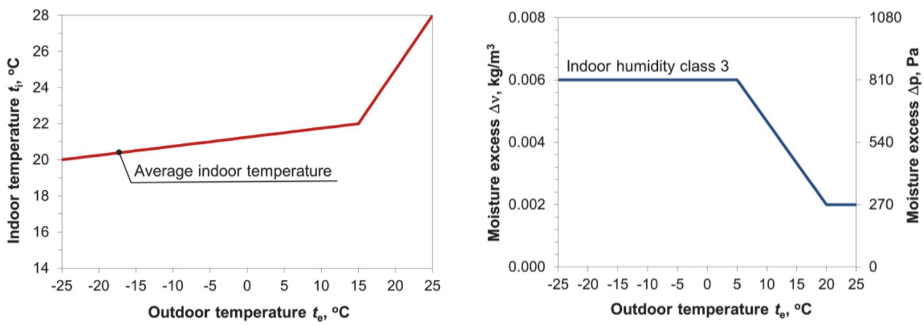


Figure 4. Dependence of indoor temperature (**left**) and design value of moisture excess (**right**) on the outdoor temperature.

As the hygrothermal performance of constructions is highly dependent on their moisture content [14,52], calculations of mold index with different initial moisture content levels of the original wall (w = 85 kg/m^3, w = 95 kg/m^3, w = 110 kg/m^3) were performed to represent the critical conditions of various periods of the start of installation works of the prefabricated timber frame insulation elements onto the existing envelope at the building site.

2.6. Energy Performance

As in many countries, including Estonia, the energy performance of buildings is defined as an indicator, expressed as energy performance value (EPV) (kWh/(m^2·a)), of the total energy delivered into the building (i.e., heating, ventilation and air conditioning (HVAC) auxiliary, cooling, ventilation, domestic hot water (DHW), lighting and appliances), multiplied with conversion factors (CF) taking into account the primary energy content and the environmental impact involved (e.g., $CF_{electricity}$ = 2.0, $CF_{district\ heating}$ = 0.9, and $CF_{efficient\ district\ heating}$ = 0.65). It is mandatory to fulfill the local decrees requirements of energy performance [53,54] for new and reconstructed by major renovation buildings. The energy performance criterion for a nZEB renovation (EPV ≤ 150 kWh/(m^2·a)) and for new buildings (EPV ≤ 125 kWh/(m^2·a) without local electricity production) was taken as the basis for evaluating energy efficiency of the studied solutions. In addition to general energy performance of buildings, the Estonian renovation grant scheme [55] sets the following criteria for renovation of apartment buildings:

- Thermal transmittance of building envelope:
    - $U_{external\ wall} \leq 0.20$ W/(m^2·K);
    - $U_{roof} \leq 0.12$ W/(m^2·K);
    - $U_{window} \leq 1.10$ W/(m^2·K);

- Installation of mechanical ventilation with heat recovery (MVHR). It means centralized plate heat exchanger or apartment based (plate or rotary thermal wheels heat exchanger) balanced ventilation (efficiency ≥80%) or exhaust ventilation with heat pump (efficiency ≥60%). In simulations, MVHR with an efficiency of 75% was used;
- Full renovation of heating system. It means new insulated pipework and hydronic radiators with thermostats, DHW system and heating unit.

Energy performance of potential renovation solutions was modeled using the energy and indoor climate simulation program IDA Indoor Climate and Energy [56]. This software allows the modeling of a multi-zone building, internal and solar loads, outdoor climate, heating and ventilation systems, and dynamic simulation of heat transfer and airflows. It is validated and the building model is calibrated against field measurements [57]. Input parameters to energy performance simulation were selected according to standard use condition from the Estonian regulations [54]:

- Indoor temperature heating set point 21 °C;
- Air flow rate for apartments with apartment-based air handling units (AHU) 0.42 l/(s·m^2) and apartments with central AHU 0.5 l/(s·m^2). Supply air temperature 18 °C;
- Standard use of DHW: 30 kWh/(m^2·a), i.e., 516 l/(m^2·a) at ΔT 50 K;
- Standard use of electricity: for appliances and lighting 29.5 kWh/(m^2·a); for circulation pumps 0.5 kWh/(m^2·a);
- Internal heat gains: occupants 15.8 kWh/(m^2·a) with a usage rate 0.6 (representing average occupancy 28.3 m^2 per person); appliances and equipment: 15.8 kWh/(m^2·a) with usage rate 0.6; lighting 7.0 kWh/(m^2·a) with a usage rate 0.1.

2.7. Cost Efficiency

The global cost calculations were applied to assess the cost effectiveness of the renovation measures [58]. The renovation cost was calculated considering financing with loan in the amount of 85% and with self-financing of 15%, which is a common practice required by banks and the renovation grant organization in Estonia for renovation projects of apartment buildings. The typical interest rate of 3% for apartment owners' associations was applied and the escalation of the delivered energy and maintenance prices was considered 1% in a year as an average [59]. The energy prices used in calculations were 0.12 €/kWh for electricity and 0.06 €/kWh for district heating, as an average market level in 2019 in Estonia. The discount period 20 years as the longest loan period for apartment owners' associations in Estonia was applied. Global cost was calculated according to Equation (4):

$$C_g(\tau) = \frac{C_i + \sum_{i=1}^{20} C_{a,i}(j) \times R_d(i)}{A_{floor}} - \frac{C_g^{ref}}{A_{floor}} \quad \left(€/m^2\right) \tag{4}$$

where $C_g(\tau)$ is the global cost referred to the starting year (€/m^2), C_i is the initial investment cost, self-financing of a renovation loan (€), $C_{a,i}(j)$ is the annual cost of year i for the component j, energy and loan payback cost (€), $R_d(i)$ is the discount rate for year i, C_g^{ref} is the global cost of the reference building (€), and A_{floor} is the net floor area (m^2).

To obtain the realistic costs for construction, installation and maintenance, the comprehensive cost estimations were taken as basis from three companies producing and installing prefabricated timber frame elements. The average initial cost of their offers was used in cost efficiency calculations.

3. Results

3.1. Hygrothermal Performance of Prefabricated Insulation Elements

Mold index M was calculated in critical points (see Figure 1) for all sets studied. Results are shown in Tables 5 and 6 where the mold index M is given at the most critical points at different initial moisture content (IMC) levels of the existing original wall with installed prefabricated insulation elements.

Table 5. Results of calculation of mold index *M* of wall constructions with MW. IMC of existing concrete wall w = 85 kg/m^3 (u = 3.7%), w = 95 kg/m^3 (u = 4.1%), w = 110 kg/m^3 (u = 4.7%). See Table 1 for description of layers D1–D5.

Wind Barrier Layer	Frame Thickness (Layer C1) IMC (kg/m^3)	Mold Index *M* (Green, Yellow, Red) at the Most Critical Points (4 or 6) C1 = 120 mm			C1 = 145 mm			C1 = 195 mm		
		85	95	110	85	95	110	85	95	110
D1	With air and vapor barrier	4	4	4	4	4	4	4	4	4
D2	B1	4	4	4	4	4	4	4	4	4
D3	(0.2 m at *RH* 85%	4	4	4	4	4	4	4	4	4
D4	≤S_d ≤	4	4	4	4	4	4	4	4	4
D5	5 m at *RH* 20%)	4	4	4	4	4	4	4	4	4
D1	Without vapor barrier B2	6	6	6	6	6	6	6	6	6
D2		6	6	6	6	6	6	6	6	6
D3		4	4	4	4	4	4	4	4	4
D4		6	6	6	6	6	6	6	6	6
D5		4	4	4	4	4	4	4	4	4
D1	With air and vapor barrier B3 (S_d ≥ 50 m)	4	4	4	4	4	4	4	4	4
D2		4	4	4	4	4	4	4	4	4
D3		4	4	4	4	4	4	4	4	4
D4		4	4	4	4	4	4	4	4	4
D5		4	4	4	4	4	4	4	4	4

Table 6. Results of calculation of mold index *M* of wall constructions with CW. IMC of existing concrete wall w = 85 kg/m^3 (u = 3.7%), w = 95 kg/m^3 (u = 4.1%), w = 110 kg/m^3 (u = 4.7%). See Table 1 for description of layers D1 ... D5.

Wind Barrier Layer	Frame Thickness (Layer C2) IMC (kg/m^3)	Mold Index *M* (Green, Yellow, and Red) at the Most Critical Points (4 or 6) C2 = 120 mm			C2 = 145 mm			C2 = 195 mm		
		85	95	110	85	95	110	85	95	110
D1	With air and vapor barrier	4	4	4	4	4	4	4	4	4
D2	B1	4	4	4	4	4	4	4	4	4
D3	(0.2 m at *RH* 85%	4	4	4	4	4	4	4	4	4
D4	≤ S_d ≤	4	4	4	4	4	4	4	4	4
D5	5 m at *RH* 20%)	4	4	4	4	4	4	4	4	4
D1	Without vapor barrier B2	6	6	6	6	6	6	6	6	6
D2		6	6	6	6	6	6	6	6	6
D3		4	4	4	4	4	4	4	4	4
D4		6	6	6	6	6	6	6	6	6
D5		4	4	4	4	4	4	4	4	4
D1	With air and vapor barrier B3 (S_d ≥ 50 m)	4	4	4	4	4	4	4	4	4
D2		4	4	4	4	4	4	4	4	4
D3		4	4	4	4	4	4	4	4	4
D4		4	4	4	4	4	4	4	4	4
D5		4	4	4	4	4	4	4	4	4

- Numbers 4 and 6 indicate the most critical points (see Figure 1):
    - o Point 4 – between original wall and air and vapor barrier layer;
    - o Point 6 – between wind barrier and insulation layer of prefabricated element;
- Mold index is categorized by colors:
    - o Green – no mold growth risk, $M < 1$;
    - o Yellow – minor mold growth risk, $1 \le M < 2$, i.e., small amounts of mold on surface (microscope), initial stage of local growth;

- o Red – high mold growth risk, $M \geq 2$, i.e., several local mold growth colonies on surface (microscope).

Results of calculations of mold indexes show that all analyzed combinations with vapor barrier with varying vapor resistance (see Table 1, position B1) or without air and vapor barrier layer (position B2) are below the critical limit ($M = 2$) of mold growth risk. Minor mold growth risk ($1 \leq M < 2$) is in constructions insulated with MW when a sheathing membrane (position D1) or gypsum board with a sheathing membrane (position. D2) as the wind barrier layer was applied. Also, with fiber cement board (position D3) and wood fiberboard (position D4) as wind barrier layers on higher insulation thicknesses and with the initial moisture content of the original concrete wall $w \geq 95$ kg/m^3 minor mold growth risk was determined. With CW some mold growth risks are noticeable with wind barriers positions D1, D2, and D3 when the initial moisture content of the original concrete wall $w \geq 95$ kg/m^3 and in case of higher thicknesses of insulation without an air and vapor barrier layer (position B2). All analyzed combinations with PE-foil (position B3) are beyond the critical limit of mold growth risk ($M \geq 2$) and therefore cannot be used in these structures. From the perspective of hygrothermal performance, MW board of ≥30 mm thickness with a special wind barrier facing is the best choice for wind barrier.

3.2. Energy Performance

The annual energy use of the reference apartment building with a total heated area of 2968 m^2 was calculated with different sets of the external wall insulation elements following criteria for renovation measures of the grant scheme [55]. The calculations were based on the IDA Indoor Climate and Energy [56] simulation program results for the reference building. The variation of total delivered energy to the renovated building with well insulated external walls is up to ±2%, see Table 7. The variation is relatively small because the building envelope is already well insulated and thus, energy for space heating is one of the smallest components of energy use.

Table 7. Influence of thermal transmittance of external walls on the use of delivered energy by the apartment building.

Thermal Transmittance of the External Walls U_c, W/(m^2·K)	Delivered Energy, kWh/(m^2·a)						
	Heat			Electricity			Total
	Space Heating	MVHR	DHW	Equipment	Fans, Pumps	Lighting	
0.22	14.0	16.9	33.3	22.5	10.5	7.0	104
0.21	13.7	16.9	33.3	22.5	10.5	7.0	104
0.20	13.4	16.8	33.3	22.5	10.5	7.0	104
0.19	13.1	16.8	33.3	22.5	10.5	7.0	103
0.18	12.8	16.7	33.3	22.5	10.5	7.0	103
0.17	12.5	16.6	33.3	22.5	10.5	7.0	103
0.16	12.2	16.6	33.3	22.5	10.5	7.0	102
0.15	11.9	16.5	33.3	22.5	10.5	7.0	102
0.14	11.7	16.5	33.3	22.5	10.5	7.0	101
0.13	11.4	16.4	33.3	22.5	10.5	7.0	101

The primary energy use depends mostly on the efficiency of district heating (the most typical heat source for apartment buildings in Estonia). After the renovation and with efficient district heating (i.e., $CF_{efficient\ district\ heating} = 0.65$) the apartment building fulfills the nZEB requirements for the new buildings [53] and with the common district heating (i.e., $CF_{district\ heating} = 0.9$) the nZEB requirements for major renovation. The results obtained contain a reasonable reserve for unforeseen energy use (e.g., user's influence), see Table 8.

Table 8. Influence of the heat source on the use of primary energy by the apartment building.

Thermal Transmittance of the External Wall U_c, W/(m^2·K)	Primary Energy Use, kWh/(m^2·a)					
	Efficient District Heating			Common District Heating		
	Heat (CF = 0.65)	Electricity (CF = 2.0)	Total	Heat (CF = 0.9)	Electricity (CF = 2.0)	Total
0.22	41.8	80.1	122	57.8	80.1	138
0.21	41.5	80.1	122	57.5	80.1	138
0.20	41.3	80.1	121	57.2	80.1	137
0.19	41.1	80.1	121	56.9	80.1	137
0.18	40.8	80.1	121	56.5	80.1	137
0.17	40.6	80.1	121	56.2	80.1	136
0.16	40.4	80.1	120	55.9	80.1	136
0.15	40.2	80.1	120	55.6	80.1	136
0.14	39.9	80.1	120	55.3	80.1	135
0.13	39.7	80.1	120	55.0	80.1	135

3.3. Cost Analysis

The unit prices of prefabricated insulation elements include production, transport, and installation costs are seen in Table 9. The unit prices of elements with different wind barrier layers (see Table 9, positions D1–D5) are given without the prices of facade system materials. The cost of facade systems (see Table 10, positions F1–F6) is given separately with maintenance cost and maintenance interval for each facade material type (per 1 m^2 of facade).

Table 9. Unit prices of prefabricated timber frame insulation elements with different insulation (MW, CW) and wind barrier materials (D1–D5) without facade materials. See Table 1 for description of layers D1 . . . D5.

Wind Barrier Layer	Unit Price of Element, €/m^2 (Frame Thickness, Layer C1 or C2)					
	120 mm		145 mm		195 mm	
	MW	CW	MW	CW	MW	CW
D1	88	85	90	87	96	93
D2	93	90	95	92	101	98
D3	96	93	98	95	105	102
D4	98	95	100	97	107	104
D5	100	97	102	99	108	105

Table 10. Unit prices, maintenance cost and intervals of maintenance of facade systems of the prefabricated elements. See Table 1 for description of layers F1–6.

Facade System	Unit Price of Facade, €/m^2	Maintenance Cost, €/m^2	Maintenance Interval, Years
F1	18	15	15
F2	22	5	15
F3	35	15	15
F4	54	5	25
F5	55	5	25
F6	56	15	20

The total initial cost (production, transport, installation) of insulation elements varies between 101 and 164 €/m^2. The selection of the facade system has the highest influence on the total initial cost: ±13%–15%. The selection of the wind barrier influences the total initial cost by ±5%–6% and the insulation material by ±1%.

Table 11 presents the change of global cost (initial cost + energy saving + annual average maintenance during 20 years after renovation (i.e., during renovation loan payback period) divided by the building's net heated area). As the influence of insulation materials cost was very small, Table 11 presents the results of sets with MW insulation only. Results are presented as the cost difference compared to the insulation element with 145 mm framing with 50 mm buffering insulation layer (see Table 1, position A) + air and vapor barrier (position B1) + MW insulation (position C1) + 30 mm MW wind barrier (position D5) + wooden boarding as facade system (positions E + F1). By combining moisture safety (Table 5) and total cost (Table 11) we can see that decreasing the total cost increases the risk of mold growth. Insulation elements with some mold growth risk ($1 \le M < 2$) were cheaper than solutions without mold growth ($M < 1$) ($p < 0.0001$ according to T-Test).

Table 11. Difference between the cost of insulation elements in relation to the set: framing 145 mm + A + B1 + C1 + D5 + E + F1. See Table 1 for description of layers A–F.

Wind Barrier Layer	Difference of Total Cost, €/m2 (Net Building Area)																	
	Frame Thickness 120 mm						Frame Thickness 145 mm						Frame Thickness 195 mm					
	F1	F2	F3	F4	F5	F6	F1	F2	F3	F4	F5	F6	F1	F2	F3	F4	F5	F6
D1	−7	−11	5	10	11	17	−7	−11	5	10	11	17	−4	−8	8	13	14	20
D2	−4	−8	8	13	14	21	−3	−7	9	14	15	21	−1	−5	11	17	17	24
D3	−2	−6	10	16	16	23	−1	−5	11	16	17	23	2	−2	14	19	20	27
D4	−1	−5	11	16	17	23	0	−4	12	17	18	24	3	−1	15	20	21	27
D5	0	−4	12	17	18	24	0	−4	12	17	18	24	3	−1	15	21	21	28

- Mold index is categorized by colors:
    - o Green—no mold growth risk, $M < 1$;
    - o Yellow—minor mold growth risk, $1 \le M < 2$, i.e., small amounts of mold on surface (microscope), initial stage of local growth.

As the facade cladding does not essentially influence the mold growth risk in the critical points, at the same time having a noticeable contribution to the total cost, the cost difference was compared without the facade system in the same way as shown in Table 11. The results in Figure 5 indicate that combinations with lower cost pose relatively higher mold growth risk.

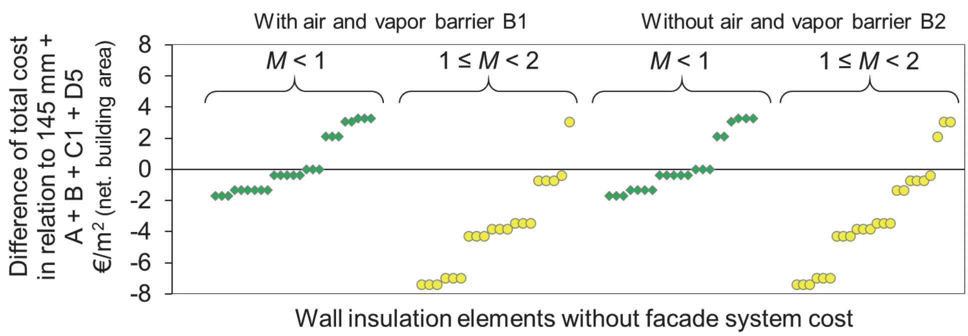


Figure 5. Influence of changing the total cost on the risk of mold growth without the contribution of facade systems to the cost of prefabricated element.

3.4. Installation and Handling Analysis

Ideas of energy renovation of old apartment buildings to the nZEB level [42,43] and answers to interviews with production companies, installation contractors, as well observations of analysis of renovation prospects with prefabricated elements, point out the most relevant problems and give guidelines for future research and development.

Accuracy of predesign and pre-installation measurements (e.g., geodesy, point-cloud, and 3D model) are crucial for a streamlined production and installation of elements because these reveal all possible deviations of openings and roughness of the original wall surface in all directions. The design of and construction works at the pilot building verified the importance of precise data about envelope roughness because the surface deviations both in vertical and horizontal directions were up to ±50 mm. Therefore, designed hanging brackets for elements should have an adjustable clearance allowing regulation of the elements in all directions during the installation to minimize the risk of time-consuming remounting of brackets in case of measurement inaccuracies.

The buffering layer has to be a light and compressible (flexible) material (e.g., MW, $\rho < 20$ kg/m^3) allowing the element to be safely pressed towards the uneven original surface and to be fixed to the load-bearing brackets while it hangs on the crane hooks and workers are standing in the high forklift basket. On the pilot building it was clearly seen that in some places the installers had quite some difficulties with pressing the element tightly to the original surface because of the variations of the surface level. Lighter MW as the buffering layer and brackets with greater adjustment clearance could help out.

Water and air tightness of horizontal joists between the elements was difficult and time-consuming to achieve as the elements are supported on a wall by each intermediate floor. Fastening of elements in the vertical direction is safer and allows designing and finishing larger gaps between elements. However, in this case, the mistakes from construction tolerances are transmitted and large differences in sizes can occur because of the existing wall roughness and irregularity.

Use of a traverse for lifting long and heavy elements by crane helps to avoid bending out or breaking an element but it can be impeded if the building has roof eaves stepping out of the wall perimeter. In that case, a forklift with a special lifting and supporting frame could be a solution. Or else, the solution could be to remove part of the roof and eaves temporarily. However, this is again an additional risk of rainwater overflow and moisture damage during construction works and needs an extra investment to prepare and remount the roofing.

Use of continual protective tarpaulins or tents on the existing envelope is obstructed because the crane or forklift must have access to wall surfaces to lift and fix the elements. Prefabricated elements must be packed to a protective foil firmly already at the factory so as to ensure their safe transport and installation without moisture impairments. The protective foil has to be removed only after the element is installed.

These are the important aspects of moisture safety and building technology that have to be analyzed, explained, and agreed upon in the contracting phase and controlled by a moisture safety expert and the owner's surveillance engineer during the installation works.

4. Discussion

The research task was to find among results obtained combinations that are most consistent with requirements of the nZEB renovation (new buildings and major renovation), considering possible hygrothermal risks and costs. Earlier studies [60–62] confirm that for deep renovation of existing external envelopes the most proper solutions are with insulation layers with low water vapor resistance (both for main insulation and wind barrier layers) and vapor barriers/retarders with varying vapor resistance capability. Solutions where the vapor resistance of the outer layer is higher and with a lower thermal resistance (e.g., sheathing membrane, strand board, or gypsum board) compared to MW or CW may cause excess humidity accumulation, which in turn might cause a higher mold growth risk with envelope degradation. It was concluded hereinbefore that in addition to energy performance it is necessary to pay special attention to moisture safety measures in the design and building processes of highly insulated buildings.

High thermal resistance and water vapor permeability of the wind barrier are key components of a well-functioning building envelope. This is validated by the results of calculations of mold index indicating a rise of mold growth risk with increasing vapor resistance of the outer layer of elements (e.g., sheathing membrane vs. MW board) and with greater insulation thickness (i.e., with the decrease of temperature and the corresponding increase of *RH* in external layers of the structure). Nevertheless, cement fiberboard gave better results in some cases compared to wood fiberboard wind barrier (although it has lower water vapor permeability and thermal resistance) because of its larger mold tolerant surface. Comparison of the use of MW and CW showed that owing to the relatively high moisture buffering capacity of CW, constructions insulated with it can withstand much higher moisture loads without substantial mold growth risk. It has been verified by other research as well [63]. Nevertheless, in case of greater thicknesses of insulation and lower water vapor permeability of surface layers, the risk of mold growth may rise with CW insulation as well.

In the renovation of the existing buildings with prefabricated insulation elements it is very important to take into consideration that the use of a vapor barrier layer with very high vapor resistance (e.g., PE-foil) may cause accumulation of built-in moisture between the original wall and the installed vapor-tight layer of the insulation element and lead to the condensate state there for a very long time (according to our studies, even up to 4–5 years) [52]. On the other hand, the decision to give up the use of a vapor control layer between the existing envelope and the installed element may result in moisture damage and mold growth related problems, particularly in the case of the moisture content of the original wall is close to saturation level (e.g., rainy periods in late summer or in autumn may cause the original wall's external layer to become very wet, up to *RH* = 100% because of wind-driven rain) and/or when the water vapor resistance of the outer layer of an element (e.g., wind barrier) is too high to let the built-in moisture dry out as fast as necessary for satisfactory hygrothermal performance of the whole system [64]. This can be seen in Tables 5 and 6, where combinations without a vapor barrier layer show a higher mold growth risk compared to solutions with a vapor barrier layer, particularly in the area behind the wind barrier layer. The reason here is the higher *RH* in critical points due to the moisture flux, which is more intensive in the structure without a vapor control layer between the original (and usually with a high content of built-in moisture) wall and the installed insulation elements.

It is very important to point out that the differences in calculated mold indexes presented are caused also by the different mold growth sensitivity classes applied for materials. Furthermore, the considered critical points were different when solutions with and without air and vapor barrier layers were compared. With air and vapor barriers (see Table 1, positions B1 and B3) the highest moisture load is in points P4 and P5 but with alternative without vapor barrier layer (see Table 1, position B2) the highest loads are in points P6 and P7 (see Figure 1 for analyzed points).

Therefore, if there are technological obstacles or other justified reasons for not to use a vapor barrier (control) layer between the original wall and the prefabricated timber frame insulation elements, it is crucial to reconsider the mold growth sensitivity class of wood or wood-/cellulose-based products with a high content of nutrients favorable for fungal growth. Because of the higher moisture flow in the absence of a vapor control layer in the direction from the original wall towards the prefabricated timber frame element, in the case of the use of untreated wood (e.g., not planed, pine or spruce sapwood) the mold growth sensitivity class 'very sensitive' should be assigned to the surfaces of timber details. In a cold and humid climate this will lead to a mold index $M \geq 2$, i.e., mold formation risks are considerably high. A strict recommendation is that a vapor control layer with varying vapor permeability (e.g., 0.2 m at *RH* 85% $\leq S_d \leq$ 5 m at *RH* 20%) should be used while the use of vapor barrier products with high vapor resistance (e.g., PE-foil, $S_d \geq 50$ m) should be avoided to keep the moisture flow controlled when additional insulation elements are installed on top of the existing moist external envelope. It is in a good agreement with and was well studied and described in our past research as well [14,52,65].

Our results showed that mold growth is avoidable and MW wind barrier board, wood fiberboard, or cement fiberboard are the preferred materials. From the production perspective, a rigid wind barrier (wood fiberboard and cement fiberboard) is preferable due to easier and quicker installation procedures. Nevertheless, these wind barriers might not be suitable if the moisture content of the original facade is high. Construction practice has shown that it is impossible to wait for better weather and to dry out the facade. Therefore, the insulation element should include a safety factor, and MW wind barrier board is the best solution because of its high water vapor permeability and thermal resistance.

Blowing in loose-fill cellulose wool (CW) is a typical method of insulation. To prevent the settling of the insulation layer of CW, the density of loose-fill insulation in walls should be much higher than commonly assumed for attics. Rasmussen [66] argued that to prevent settling the density of loose-fill

CW insulation in the wall should be ρ ≥ 65–75 kg/m^3 to compensate for any humidity cycling and creep. However, he did not consider the vibration due to transportation (which is unavoidable for prefabricated insulation elements). Therefore, the density of loose-fill insulation for prefabricated insulation elements should be much higher than for attics. Higher density requires more material, resulting in higher cost and heavier elements.

Building contractors and producers of insulation elements have given critical feedback about the design and installation of insulation elements. The most objective and practical of them stress indispensable need for a pre-installation phase: well-prepared measurement of the existing situation and translation of the results into detailed and precise design documentation. Clients and moisture safety experts point out the importance of how materials are handled during transportation to the building site and especially during the ongoing works under changing and challenging weather conditions. The use of protective foils, pallets, and well-planned precautionary actions before precipitation is a must to avoid later problems with moisture damage, degradation of structures, and unsatisfactory indoor climate.

Facade cladding choices (e.g., wooden or plastic boarding/siding, metal profile sheets, cement fiberboards, facade stone cladding, etc.) are rather made by personal preferences of each customer. The preferred materials are dissimilar in unit price as well as mounting and maintenance costs. However, these costs may account for a large proportion of the total renovation budget. Therefore, circular use of materials could be one way of reducing the cost of facade cladding.

In comparison of the energy performance on the basis of variation of total delivered energy we can see that differences were relatively small because the energy for space heating was one of the smallest components of total energy use. However, it is important to see that in calculations indoor temperature set point was 21 °C. It was shown by preceding studies [67–69] that indoor temperature set point used is higher, typically 22 °C for post-renovation situation. That a 1 °C rise will affect the amount of delivered energy for space heating in average +33%, EPV for +1.2–+1.4% and the global cost for +1.0–+1.3%.

Compared to conventional solutions of energy refurbishment (e.g., ETICS or analogues), the cost level of the analyzed prefabricated elements for the end-user is still slightly higher (about 101–164 €/m^2). The current market prices of the ETICS with expanded polystyrene (EPS) insulation are around 90–100 €/m^2 and with rendered MW around 100–120 €/m^2. This cost difference together with some shortage of expertise of participants is described also by other researchers as the main reason why prefabricated insulation elements are not yet in a competitive market position [70,71]. Renovation activity must be increased to a very large extent to fulfill EU decarbonization targets. Estonian practice has shown [72] that increased renovation volumes create new problems such as shortage of contactors, construction workers, and construction materials, which results in increased renovation costs. The ETICS and other rendering methods have been on the market already for many decades without moving forward towards industrialized production. The main way to increase the efficiency and reduce the cost is to raise the automation level and to find means of unification of products for faster design, mass production and installation. Other industries have shown that industrialization and mass production decrease the costs. Therefore, the prefabricated elements will obviously have cost advantages in the future.

5. Conclusions

A complex method of analysis and selection to find the most appropriate set of prefabricated insulation elements for major renovation of apartment buildings was introduced in this research. The most consistent sets, based on hygrothermal performance, handling and production characteristics and reasonable cost, were presented.

Mineral wool board with special wind barrier facing is the best material for wind barriers from the perspective of hygrothermal performance. In cold and humid climates PE-foil cannot be used as an air and vapor barrier layer in prefabricated insulation elements as it does not allow constructional moisture to dry out and causes condensation and mold growth. Compared to mineral wool, cellulose insulation has advantages concerning hygrothermal performance, but its installation density should be high ($\rho \geq 65$ kg/m^3) to avoid settling due to humidity cycling, creep, and vibration on transportation from the production facilities to the building site.

The variation of thermal transmittance of a well-insulated external wall has minor influence on the energy performance of the building. It is possible to renovate an apartment building to correspond to the new building nZEB level with efficient district heating and to fulfill the nZEB requirements for renovation in the case of common district heating being used.

Cost analyses showed that materials affecting moisture safety and energy performance do not influence the total cost too much. Therefore, it is possible to select the best materials from the perspective of hygrothermal and energy performance without increasing the renovation price noticeably. The facade cladding had the highest influence on the initial cost of the insulation element (±13%–15%). This means that the materials having the greatest effect on the hygrothermal performance of the building envelope have smaller influence on the initial cost. It is possible to guarantee moisture safety without paying a high relative difference cost. Decreasing the global cost of elements would increase the mold growth risk.

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Errata

Pihelo, P. (2020) Hygrothermal Performance of Prefabricated Timber Frame Insulation Elements for Deep Energy Renovation of Apartment Buildings. Doctoral thesis, Tallinn University of Technology.

Location:

In publication V (Commissioning of Moisture Safety of nZEB Renovation with Prefabricated Timber Frame Insulation Wall Elements. Wood Material Science and Engineering, published online: 03 July 2019), Table 2, page 6

Was:

Table 2. Moisture content measurements of samples of PCLP during construction, before installation of prefabricated wall elements (May-June 2017).

Sample No. *	1-12	3-22	4-42	5-42	1-41	3-31	4-11	5-11
Diameter d, mm	43.5	43.3	43.4	43.3	94.2	94.5	93.9	94.1
Moisture content *w*, kg/m^3	43.3	62.7	63.1	54.9	53.9	76.7	53.6	60.7
Moisture content *u,* vol.%	4.3	6.3	6.3	5.5	5.4	7.7	5.4	6.1

* Sample No. describes the floor (1-, 3-, etc) and relative placement of the PCLP element on the wall (-12, -22 etc).

Should be:

Table 2. Moisture content measurements of samples of PCLP during construction, before installation of prefabricated wall elements (May-June 2017).

Sample No. *	1-12	3-22	4-42	5-42	1-41	3-31	4-11	5-11
Diameter d, mm	43.5	43.3	43.4	43.3	94.2	94.5	93.9	94.1
Moisture content *w*, kg/m^3	43.3	62.7	63.1	54.9	53.9	76.7	53.6	60.7
Moisture content *u,* vol.%	2.12	2.95	2.93	2.63	2.33	3.55	2.45	2.98

* Sample No. describes the floor (1-, 3-, etc) and relative placement of the PCLP element on the wall (-12, -22 etc).

Corrected data, adapted from publication V, Table 2, is presented in the thesis in Table 4.1.

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Publications / Teaduspublikatsioonid

Articles in peer-reviewed scientific journals
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Pihelo, P., Kalamees, T., 2016. The Effect of Thermal Transmittance of Building Envelope and Material Selection of Wind Barrier on Moisture Safety of Timber Frame Exterior Wall. Journal of Building Engineering 6, 29–38. 10.1016/j.jobe.2016.02.002

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