RIGA TECHNICAL UNIVERSITY

Edīte Biseniece

SUSTAINABLE PRESERVATION OF HISTORIC BUILDINGS

Summary of the Doctoral Thesis

RTU Press
Riga 2021

RIGA TECHNICAL UNIVERSITY
Faculty of Electrical and Environmental Engineering
Institute of Energy Systems and Environment

Edīte Biseniece
Doctoral Student of the Study Programme "Environmental Science"

SUSTAINABLE PRESERVATION OF HISTORIC BUILDINGS

Summary of the Doctoral Thesis

Scientific supervisor
Professor Dr. sc. ing.
ANDRA BLUMBERGA

RTU Press
Riga 2021

Biseniece, E. Sustainable Preservation of Historic Buildings. Summary of the Doctoral Thesis. Riga: RTU Press, 2021. 37 p.

Published in accordance with the decision of the RTU Promotion Council “P-19” of 7 May 2021, Minutes No. 139.

https://doi.org/10.7250/9789934226533
ISBN 978-9934-22-653-3 (pdf)

DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (Ph. D.), the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council on 30 August 2021 at 2 p.m. at the Faculty of Electrical and Environmental Engineering of Riga Technical University, 12 k-1 Azenes Street, Room 212.

OFFICIAL REVIEWERS

Professor Dr. sc. ing. Gatis Bažbauers
Riga Technical University, Latvia

Professor Dr. sc. ing. Aigars Laizāns
Latvia University of Life Sciences and Technologies, Latvia

Professor Dr. ing. Uli Jakob
Stuttgart University of Applied Sciences, Germany

DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for review to Riga Technical University for the promotion to the scientific degree of Doctor of Science (Ph. D.) is my own. I confirm that this Doctoral Thesis had not been submitted to any other university for the promotion to a scientific degree.

Edīte Biseniece……………………………. (signature)

Date: ………………………

The Doctoral Thesis has been written in English. It consists of an Introduction; 3 chapters; Conclusions; 44 figures; 17 tables; the total number of pages is 162. The Bibliography contains 77 titles.

CONTENTS

INTRODUCTION

There has been large focus on energy efficiency and indoor comfort in buildings sector. People spend almost 80 % of their life indoors. To reach energy and climate goals, energy efficiency of existing buildings should be dramatically incised. The most significant part of buildings in EU was built in times when energy performance standards were not in place. These buildings, in most cases, have high level of air leakage and inadequate insulation. Buildings have high energy consumption for heating, ventilation, and air-conditioning systems and decrease occupant comfort and indoor air quality. The EU building sector is the single largest energy consumer in the EU, accounting for 40 % of EU energy consumption and 36 % of the greenhouse gas emissions. Therefore, it represents a huge potential in energy savings. According to the European Commission, the annual renovation rate of the building stock varies from 0.4 % to 1.2 % in the Member States, but this rate will need at least to double to meet the targets set by the European Commission the greatest challenge of which is to perform cost-effective building retrofit projects, as it is a multi-objective problem with many measures and constraints that often are competing.

The biggest challenges during the renovation of buildings occur when it comes to retrofitting historic buildings where the facade cannot be modified to maintain its unique architectural appearance and integrity. In many European countries, historic buildings account for a significant part with a high potential for energy savings. In Latvia alone the share of historic buildings in the residential sector makes up to 22 %

The conservation of cultural values of historic buildings and improving their energy performance can be first seen as somewhat contradictory. Indeed, thermal insulation cannot always be applied on the exterior walls, e.g., due to the preservation of the facade. In that case, interior insulation measures should be investigated and currently represent the most challenging retrofit measure in historic buildings. Applying interior insulation significantly modifies the hygrothermal performance of walls and, consequently, may induce a risk of interstitial condensation, frost damage, mould growth, and other damage patterns. The associated damage risks regarding the increase of moisture and reduced wall temperature should be evaluated before starting the renovation. There is a need to develop new methods of implementing energy efficiency measures in these buildings.

Hygrothermal performance of internally insulated wall strongly depends on its material parameters. The diversity of historically used construction materials across regions, countries and globally creates a need for the creation of a material properties database that can sufficiently provide for the needs of safe renovation with internal insulation.

Most remaining historic buildings today are brick buildings, especially in the cities of the Baltic Sea region. Bricks in unprotected masonry are exposed to moisture and large temperature fluctuations during different seasons. Researchers have proven that moisture not only significantly reduces indoor comfort level but may cause significant deterioration of the construction materials leading to loss of mechanical resistance and stability.

There is a lack of understanding of historical building performance in the industry and policy and a lack of connection between good research, standards, certification processes, guidance and practice.

This work covers the theme of refurbishment measures in historical buildings – the specific measures like inside insulation and risks that can arise because of it. This is done by simulation using computer models that require appropriate input data for material properties gained by laboratory tests. Simulation models are validated by long term in situ measurements.

This information may be further used to develop practical, comprehensive decision guidelines to improve the energy performance of historic buildings by investigating interior insulation measures.

Research Topicality and Hypothesis

The research is investigated through the following hypothesis.

Hypothesis 1: It is possible to predict the hygrothermal performance of internally insulated structure by means of dynamic simulation, thus allowing to assess and prevent risks associated with the restoration of historic buildings.

Hypothesis 2: It is possible to reduce energy consumption in historical buildings by applying internal insulation, preserving its cultural and historical value without creating additional risks of structural damage.

Currently, there are several challenges for the energy efficiency improvements of historic buildings. They all are related to internal insulation and moisture transport within the wall. In the case of internal insulation, the original wall remains on the cold side of the structure, which induces a reduction of any potential drying of the wall. Undesirable moisture conditions might lead to mould growth, condensation of water vapour, especially interstitial condensation, the risk of water penetration from the outside due to wind-driven rain, the risk of frost damage, and hydration of salts. Therefore, internal insulation should not be used without an accurate evaluation of the potential moisture conditions.

Aim and Objectives

The aim of the Thesis is to offer safe and effective solutions for internal insulation systems of historic masonry buildings.

The main objectives for achieving the aim are:

1) to perform construction material testing and analyses of test wall in a laboratory environment in order to determine the factors influencing the accumulation of moisture and the risks associated with it;
2) to predict hygrothermal conditions of internally insulated masonry building using dynamic simulation program and to validate said models based on long-term measurements in internally insulated case buildings;
3) to estimate potential energy savings using dynamic simulation program;

4) to introduce a scientifically justified evaluation method and criteria for decision making about internal insulation in historical buildings and risks associated with it.

The objectives have been met by the literature review and means of various studies: both in a laboratory and the case buildings by performing dynamic simulations for building energy performance and hygrothermal performance of internally insulated masonry. Figure 1 represents tasks performed within the research and how they are connected.

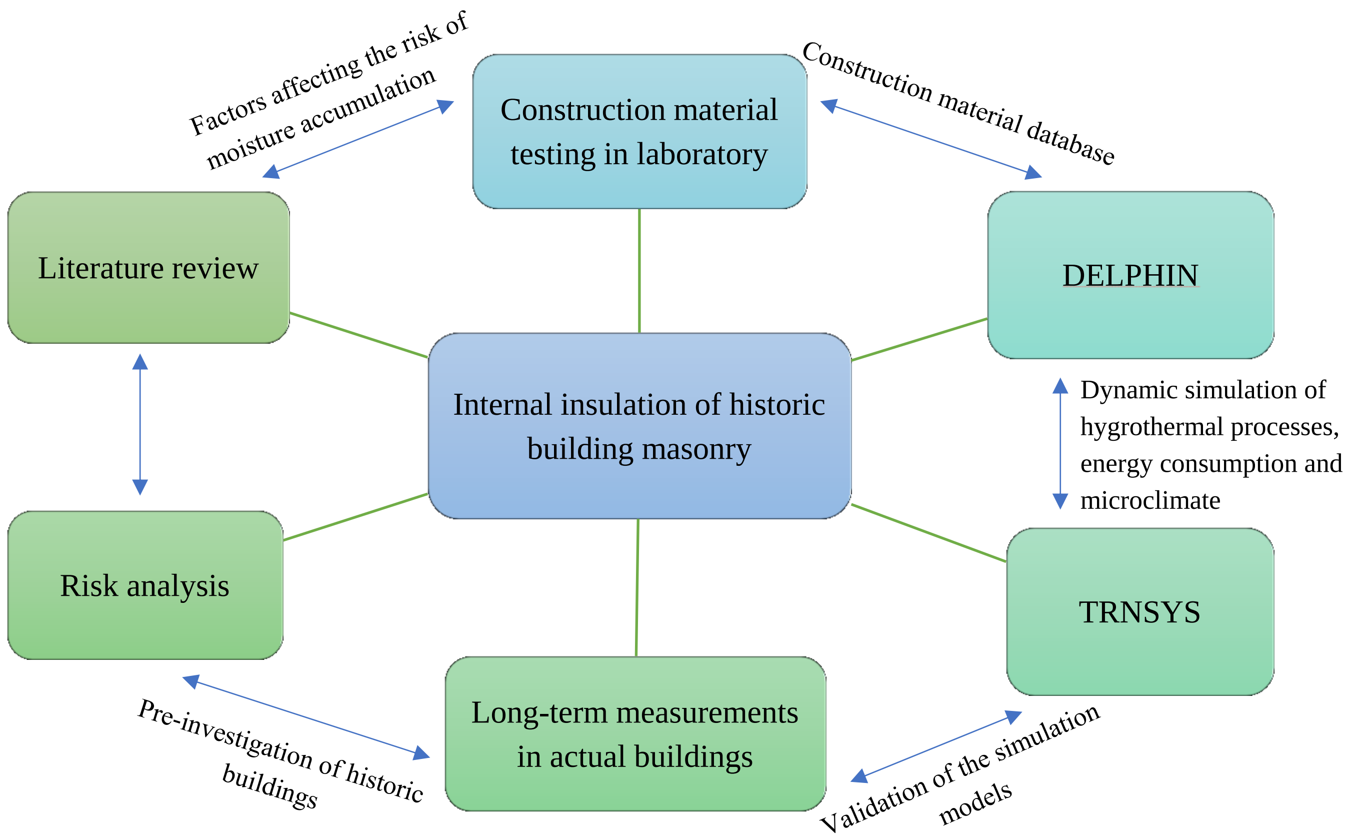


Fig. 1. Tasks performed within the research.

Scientific Novelty and Scientific Significance

Until now, hygrothermal performance of the external walls of historic buildings has not been widely studied in Latvia. The same goes for historical materials. Studies are available for separate building structural elements of the Riga Stock Exchange, Riga City Council, mainly for restoration needs, but they do not provide and in-depth insight into hygrothermal properties or materials used.

The created dynamic calculation models were validated by comparing the measurement data with calculation data, using verification tests and comparing the obtained calculation data with the results of dynamic modelling programs.

The dynamic simulation models have been approbated by performing surveys of historical masonry walls, long-term humidity and temperature measurements in walls and rooms.

A variety of construction materials were tested in the laboratory, and other test results were used to model the dynamic moisture transport in the massive historic walls.

Practical Significance

During the research, techniques have been developed and modelling possibilities tested, which allows for planning a safe renovation of historic buildings using internal insulation. Thus, the preserving architectural and cultural value of the building facade while reducing heat loss through the building's external envelope. Consequences of internal insulation with the help of long-term measurements in case buildings and tests in the laboratory together with dynamic simulation.

This research will serve as a basis for the development of safe, effective, and comprehensive decision guidelines to improve the energy performance of historic buildings by applying internal insulation.

Approbation of the Research Results

1. Kamenders A., Kašs, K., Biseniece E., Lupkina L., Bažbauers J. Quality management in energy performance contracting projects. (2018) Energy Procedia, 147, 2018, 636–640.
2. Biseniece E., Freimanis R., Purviņš R., Grāvesliņš A., Pumpurs A., Blumberga A. Study of Hygrothermal Processes in External Walls with Internal Insulation. (2018) Environmental and Climate Technologies, 22, 22–41.
3. Biseniece E., Žogla G, Kamenders A., Purviņš R., Kašs K., Vanaga R., Blumberga A. Thermal performance of internally insulated historical brick building in cold climate: A long term case study. (2017) Energy and Buildings, 152, 577–586.
4. Purviņš R., Kamendere E., Blumberga A., Laboratory investigation of Latvian historic brick and measurements of water movement in historic masonry walls. (2017) Energy Procedia, 113, 327–332.
5. Kašs K., Blumberga A., Blumberga D., Žogla G., Kamenders A., Kamendere E. Pre-assessment method for historical building stock renovation evaluation. (2017) Energy Procedia, 113, 346–353.
6. Kamendere E., Grava L., Zvaigznitis K., Kamenders A., Blumberga A. Properties of bricks and masonry of historical buildings as a background for safe renovation measures. (2016) Energy Procedia, 95, 119–123.
7. Blumberga A., Kašs K., Kamendere E. A review on Latvian Historical Building Stock with Heavy Walls. (2016) Energy Procedia, 95, 17–21.
8. Kamenders A., Vanaga R., Kamendere E., Blumberga A. Cost-optimal energy performance level for apartment buildings in Latvia. (2014) Proceedings of the 27th International Conference on Efficiency, Cost, Simulation and Environmental Impact of Energy Systems, ECOS 2014.

9. Biseniece E., Freimanis R., Kamenders A., Blumberga A. Historic single-family home made of dolomite stone with internal insulation – Long-term case study in a cold climate (prepared for submission in 2021).

Other Scientific Publications

1. Kamendere E., Žogla G., Kamenders A., Ikaunieks J., Rochas C. Analysis of mechanical ventilation system with heat recovery in renovated apartment buildings. (2014) Energy Procedia, 72, 27–33.
2. Kamendere E, Zandeckis A., Kamenders A., Ikaunieks J., Rochas C. Mechanical ventilation with heat recovery system in renovated apartment buildings. (2014) Agronomy Research, 12, 491–498.

Reports at Scientific Conferences

1. Biseniece E., Freimanis R., Purviņš R., Grāvesliņš A., Pumpurs A., Blumberga A. Study of Hygrothermal Processes in External Walls with Internal Insulation. (2018) *International Scientific Conference of Environmental and Climate Technologies, CONECT 2017,* Latvia, Riga, May 10–12, 2017.
2. Purviņš R., Kamendere E., Blumberga A. Laboratory investigation of Latvian historic brick and measurements of water movement in historic masonry walls. (2017) *International Scientific Conference of Environmental and Climate Technologies, CONECT 2016,* Latvia, Riga, October 12–14, 2016.
3. Kašs K., Blumberga A., Blumberga D., Žogla G., Kamenders A., Kamendere E. Pre-assessment method for historical building stock renovation evaluation. (2017) *International Scientific Conference of Environmental and Climate Technologies, CONECT 2016,* Latvia, Riga, October 12–14, 2016.
4. Kamendere E., Grava L., Zvaigznitis K., Kamenders A., Blumberga A. Properties of bricks and masonry of historical buildings as a background for safe renovation measures. (2016) *International Scientific Conference of Environmental and Climate Technologies, CONECT 2015,* Latvia, Riga, October 14–16, 2015.
5. Blumberga A., Kašs K., Kamendere E. A review on Latvian Historical Building Stock with Heavy Walls. (2016) *international Scientific Conference of Environmental and Climate Technologies, CONECT 2015,* Latvia, Riga, October 14–16, 2015.
6. Kamendere E., Žogla G., Kamenders A., Ikaunieks J., Rochas C. Analysis of mechanical ventilation system with heat recovery in renovated apartment buildings. *International Scientific Conference of Environmental and Climate Technologies, CONECT 2014,* Latvia, Riga, October 14–16, 2014.
7. Kamendere E, Zandeckis A., Kamenders A., Ikaunieks J., Rochas C., Mechanical ventilation with heat recovery system in renovated apartment buildings. *5th International Conference "Biosystems Engineering 2014"* Tartu, Estonia, May 8–9, 2014.

8. Kamenders A., Vanaga R., Kamendere E., Blumberga A., Cost-optimal energy performance level for apartment buildings in Latvia. 27th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, ECOS 2014, Abo Akademi University Turku, Finland. June 15–19, 2014.

Monograph

1. Blumberga, A., Blumberga, D., Biseniece, E., Kamenders, A., Kašs, K., Vanaga, R., Žogla, G. Ēku energoefektivitāte: vakar, šodien un rīt. Riga: RTU Press, 2017. 352 p. ISBN 978-9934-10938-6.

Thesis Outline

The Doctoral Thesis is based on nine thematically unified scientific articles. All of them are accessible in international citation databases.

The Doctoral Thesis consists of introduction and three sections: literature review, research methodologies and results and conclusions. It all revolves around three main topics: 1) energy efficiency of buildings, preservation of historic buildings and reducing its energy consumption; 2) used materials and their impact on moisture transport processes; 3) hygrothermal performance of internally insulated historic buildings.

The introduction presents the aim of the Doctoral Thesis and the scientific and practical importance of the work. It also includes the approbation of published research results and also publications and the monograph related to building energy efficiency.

The first section of the work includes a literature review of the main topics presented in this research, also outlining the problem and significance of the topic. The second section describes the used methods. The third sections present the results of laboratory studies and long-term measurements in case buildings and the results of dynamic simulations and correlation with long-term measurements. Finally, conclusions are given, which answers the hypothesis. The Bibliography contains 77 titles.

1. METHODOLOGY

1.1. Pre-Investigation Analysis

The pre-investigation analysis includes an analysis of construction details and damages, a report on moisture status, salt presence and construction material parameter determination for hygrothermal simulations. Additionally, preliminary study of hygrothermal behaviour of an internally insulated wall in a laboratory environment is included in this chapter.

Technical Assessment and Moisture Measurements

In order to quantify the technical condition of the building, a six-point scale condition assessment shown in Table 1.1 is adapted. As historic buildings are examined in-situ, it is possible to evaluate the performance of each building against each of the possible modes of failure. By evaluating all the parameters, it is possible to compare different buildings regarding the buildings performance and cumulative score.

Table 1.1

Six-point Technical Condition Assessment Scale for Various Historic Building Elements

Rating	Condition	Description
6	Very bad	Severe damage is detected, and it is necessary to partly or entirely replace the element
5	Bad	Mayor repairs are necessary to rehabilitate the construction element
4	Poor	Some repairs are necessary
3	Fair	Some damage is detected, condition-based maintenance is necessary
2	Good	Some damage is detected, preventive maintenance is necessary
1	Excellent	Only signs of physical wear can be detected
0	Outstanding	No damage has been detected

To gain more information about the condition of the building, especially moisture content in the walls, non-destructive measurements can be used. Non-destructive measurements are made by dielectric moisture indicators Trotec T600 and Trotec T650, which determine distributions of moisture content up to 40 mm (T600) and up to 300 mm (T650) from the surface. The measured values are not a quantitative moisture measurement, but they can be interpreted as indicators: dry (less than 40 digits), damp (40–80 digits) and wet (over 80 digits). Measurements can be made from the inside and from the outside.

For the first batch of non-destructive moisture measurements, ten buildings located in Riga and built in the same time period (1890–1940) from clay bricks were chosen. Later, more frequent non-destructive moisture measurements were performed for another three buildings located in Riga. A macro-based tool was developed in Microsoft Excel to display moisture levels for each measurement point over time, which allowed the analysis of trends of moisture level and moisture distribution within three by three plot both for the 4 cm and 30 cm depth.

To understand the meaning of the non-destructive measurement results, they were compared to destructive measurements. With the destructive moisture content measurement method holes are drilled, using a 12 mm diameter drill. The moisture content then is measured by weighting wet and dry brick dust.

Historic Construction Material Parameters

To determine historic construction material properties, brick and stone samples taken from historic buildings were tested in the laboratory. The main characteristics and respective test methods are summarised in Table 1.2. In addition to the standard measurement methods, other methods, which mostly are modified standard methods, developed by researchers of the Dresden University of Technology for the determination of material parameters, were used. To obtain this necessary information, brick or stone samples are carefully removed from the building and taken to the laboratory. The laboratory data are determined by a series of tests. Depending on test, 3–22 specimens have to be prepared (cut, pre-conditioned) in order to receive information on the variance of the properties and to minimize irregularity effects.

Table 1.2

Essential Characteristics of the Historic Material Samples and Corresponding Test Methods

Name of the material characteristic	Symbol (unit)	Name of the corresponding experiment
Parameters to support the technical assessment of building:		
Compressive strength	N/mm^2	EN 772-1+A1:2015 (destructive) *СКБ СТРОИПРИБО ИПС МГ 4.03* apparatus (non-destructive)
Density	m^3	EN 772-13:2000
Water absorption	%	EN 772-21:2011
Freeze thaw resistance	cycles	LVS 405:2002
Soluble salt content		Strip test
Parameters for hygrothermal performance:		
Bulk density	ρ_b (kg/m^3)	Via dimensions and weight of the sample
Open porosity	Θ_{por} (m^3/m^3)	Calculated from density
Thermal conductivity	λ_{dry} (W/(m K))	Heat flux measurement (plate apparatus)
Heat storage capacity	c (J/(kg K))	Calorimeter experiment
Dry-cup vapour diffusion	μ_{dry} (–)	Dry-cup measurement (EN 12572)
Wet-cup vapour diffusion	μ_{wet} (–)	Wet-cup measurement (EN 12572)
Water uptake coefficient	A_w ($kg/m^2\sqrt{s}$)	Water uptake experiment (EN 15148)
Capillary saturation moisture content	Θ_{cap} (m^3/m^3)	Final value of the water uptake experiment (EN 15148)
Sorption moisture content	$\Theta_l(\varphi)$ (m^3/m^3)	Exsiccator/Deciccator (EN 12571)

Laboratory Study of Internally Insulated Wall

An experimental setup for the hygrothermal behaviour tests was built in the laboratory. Four different insulation materials – expanded polystyrene board, wood fibreboard, mineral wool and granular aerogel, two types of vapour barriers, and gypsum board, were used in this study. The base wall was built from historic bricks collected from the demolition site of a historic building built around 1900 at 6 O. Vācieša Str., Riga, Latvia, with lime-cement mortar. For indoor and outdoor conditions, simulation double climatic chambers were used.

A test wall with four double leaf masonry patterns (25 cm × 28 cm × 51 cm) was built and inserted inside this chamber. The thickness of insulation materials was selected based on the average U-value of 0.35 W/(m^{2}K) for all four wall patterns. All patterns were covered with gypsum board from the indoor side. Vapour barriers with different equivalent air layer thicknesses (sd values 4.5 m and 12 m) were used. Two test rounds were carried out, the test condition of each round is given in Table 1.3. Relative humidity and temperature were measured between insulation and masonry (on the middle of the brick) and in both chambers with eight temperature sensors and five relative humidity sensors. The time step of both measurements is 1 minute.

Table 1.3

Test Conditions of Test Rounds

Test conditions	Test 1	Test 2
Preconditioning period length, days	10	8
Preconditioning temperature / relative humidity	+23 °C / 25 %	Room conditions
Length of the test, days	22	23
Test conditions:		
Indoor temperature / relative humidity	+19.5 °C to +20.5 °C / 53–56 %	+19.5 °C to +20.5 °C / 53–56 %
Outdoor temperature / relative humidity	–0.5 °C to +0.5 °C / 80–90 %	+2.5 °C to +3.5 °C / 80–90 %

The 2-dimensional hygrothermal behaviour in transient conditions of the base wall and three different insulation materials were analysed using 2-dimensional software DELPHIN. Granulated aerogel was not simulated, as it is not available in the material database. Prior to the experiments, the density and open porosity of bricks were tested in the laboratory. These two parameters were used as indicative values to select suitable brick from the DELPHIN database.

1.2. Energy Consumption

Energy consumption can be calculated by hand according to the method described in ISO standard 13790:2008, taking into consideration national regulations or simulated using available simulation tools.

During the research, calculations were performed for ten different historic buildings during the pre-investigation stage to understand the correlation between their technical condition and energy consumption. However, dynamic simulation tool TRANSYS was used for case buildings 2 and 3 to evaluate the possible energy savings.

All three case buildings had three scenarios simulated/calculated:

1: The building as it was before renovation, i.e. without internal facade insulation;

2: The building with the implementation of internal facade insulation in above ground floors.
3: The building with other energy saving measures (basement ceiling and roof insulation, change of windows).

Since there are many unclear parameters (internal heat gains, usage characteristics of the building, air change rate, etc.) that have to be taken into consideration in the calculations, several assumptions concerning indoor temperature and relative humidity, ventilation, and heat gains have been made for each of the case buildings.

1.3. Hygrothermal Performance of Internally Insulated Construction

Three historic buildings (Fig. 1.1) were chosen as case buildings for this research. They differ by intended use, used construction materials and size. An overview of the buildings is given in Table 1.4.

a)  b)  c) 

Fig. 1.1. a) Case building 1; b) Case building 2; c) Case building 3.

Case buildings 1 and 2 had complete renovation with insulation of walls, roof, basement ceiling, change of windows and change of heating system. During this research, the owners of Case building 3 continuously postponed the completion of renovation work due to financial problems. At the time of research, internal insulation (50 mm mineral wool) on the above ground floors were installed, and the basement was insulated from the outside.

Table 1.4

Overview of the Case Buildings

	Location	Type	Year of construction	Heated area, m^2	Volume, m^3	Year of renovation
Case building 1	8 Maskavas Street, Riga	Other	1930	64.8	252.7	2013
Case building 2	Sece parish, Aizkraukle county	Single-family house	1893	339	870.34	2006 and 2015
Case building 3	6 O. Vācieša Street, Riga	Educational building	1910	2410	9142	2018 (done partly)

In all case buildings, in-situ measurements were performed for two external walls. Internal insulation systems of measured walls in more details are described in Table 1.5.

Measurements performed in each case building are summarized in Table 1.6. Moreover, an example of the measurement setup of Case building 2 is given in Fig. 1.2.

Table 1.5

Internal Insulation Systems Applied to the Case Buildings

Case buildings	Insulation system	Material	Thickness, mm	Thermal conductivity λ, W/(mK)	Calculated heat transfer coef. U, W/(m^{2}K)
Case building 1	System 1	Self-cleaning facade paint Lotusan	–	–	0.13
		Silicate bricks	510	0.8	
		Vacuum insulation panels	50	0.008	
		Vapour barrier	–	–	
		Plasterboard	25	0.21	
		Interior decoration	–	–	
	System 2	Self-cleaning facade paint Lotusan	–	–	0.27
		Silicate bricks	510	0.8	
		Aerogel	50	0.018	
		Vapour barrier	–	–	
		Plasterboard	25	0.21	
		Interior decoration	–	–	
Case building 2	System 1	Dolomite	600	2.2	0.208
		Existing plaster	20	0.87	
		Mineral wool	200	0.035	
		Vapour barrier	–	–	
		Plasterboard	12.5	0.21	
		Interior decoration	–	–	
	System 2	Dolomite	600	2.2	0.211
		Existing plaster	20	0.87	
		Mineral wool	150	0.035	
		Vapour barrier	–	–	
		Plasterboard	12.5	0.21	
Case building 3	System 1 and System 2	Existing masonry	660	0.64	0.375
		Levelling mortar layer / existing plaster	10	0.87	
		Mineral wool in timber frame	50	0.035	
		Vapour barrier	–	–	
		Plasterboard	25	0.21	
		Interior decoration	–	–	

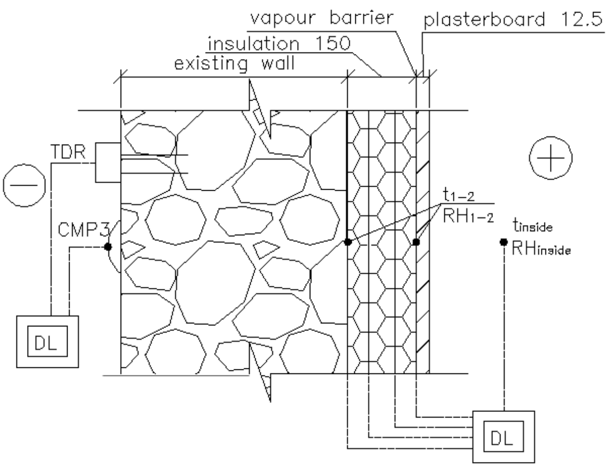
The measurement period in Case building 1 was January 2014 to November 2014, but in Case building 2 – December 2017 to January 2019 and for Case building 3 – February 2018 to November 2018.

Heat flux measurements and temperature measurements were used to obtain the measured heat transfer coefficient of the walls insulated with aerogel and vacuum insulation panel (VIP) in Case building 1 and with mineral wool (150 mm and 200 mm) in Case building 2. Moisture content was measured only in Case building 2 – in dolomite masonry in the depth of 300 mm from the outer surface.

Table 1.6

Long-Term Measurements in Each Case Building

	Case building 1	Case building 2	Case building 3
Temperature at interfaces	Yes	Yes	Yes
Relative humidity at interfaces	–	Yes	Yes
Temperature inside	Yes	Yes	Yes
Relative humidity inside	Yes	Yes	Yes
Volumetric water content	–	Yes	–
Heat flow	Yes	Yes	–



a)


b)

Fig. 1.2. a) Measurement setup for Case building 2 (*t* – temperature; *RH* – relative humidity; CMP3 – sun radiation, DL – data logger, TDR – volumetric water content.); b) measurement points in the living room wall.

To evaluate the hygrothermal performance of the external walls of Case buildings 1 and 2, simulation of heat and moisture transport processes was done using analytic hygrothermal simulation tool DELPHIN.

In all cases, accurate climatic data obtained from weather stations operated by State Ltd "Latvian Environment, Geology and Meteorology Centre" were used. In the simulation of Case building 1, indoor boundary conditions (temperature and relative humidity) are assumed constant: 20 °C and 50 %, while in the case of Case building 2, data gained from in-situ measurements were used.

The output from simulation models was defined as average relative humidity and temperature between construction layers and at surface of the wall from the inside and from the outside.

To validate the reliability of hygrothermal conditions in internally insulated historic building, the correlation analysis was performed to compare results of in-situ measurements and simulation results.

2. RESULTS

2.1. Pre-Investigation Analysis

Technical Assessment and Moisture Measurements

Technical assessment together with energy audit was done for 10 historic buildings in different locations in Latvia. Six of them are residential buildings, three – public, one – educational and one castle. All buildings are entirely listed as historical buildings and protected with no possibilities to make any changes which would compromise their outer appearance or buildings with partly protected facades that have some flexibility regarding retrofit measures. For all buildings, energy audit was done to estimate their energy consumption for space heating.

To analyse if there is a substantial relation between the assessment of building's technical condition and building's energy consumption, the regression analysis between the two parameters was carried out. The obtained graph can be seen in Fig. 2.1.

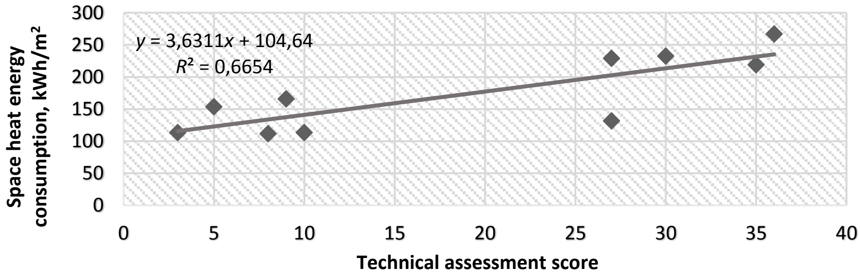


Fig. 2.1. Consumption of space heating energy related to building's technical assessment.

There is a statistically significant relation between building's technical assessment score. Using historical building pre-assessment tool, it is possible to identify the main problems and evaluate them. Primarily, buildings with higher specific energy consumption and higher technical assessment scorers should be renovated, as these buildings are in poor technical condition with a considerable potential to deteriorate even further, as well as by saving heat energy, it would be possible to make the renovation process more profitable. All inspected buildings have damages caused by moisture. Examples of damages that moisture causes are given in Fig. 2.2 and include damp rise, collapse of brickwork, algae growth, salt efflorescence.

Fig. 2.2. Damages caused by moisture in masonry of historic buildings.

The results of non-destructive moisture measurements in masonry represent the moisture migration in the masonry from the interior very well. It takes place from bottom-up through the pores to the exterior. It is common for moisture to decrease diagonally up towards the open corner. For building scale moisture levels were generally lower in building corners than in the central part, and open corners had more fluctuations than corners connected with other buildings.

In Case building 1, non-destructive measurements were compared by destructive measurements. Non-destructive measurements showed that the deeper layers of the wall (40 mm from the inside surface) were damp and near the ground even wet, the wall at 300 mm depth (from the inside) was dry except for two damp points (Fig. 2.3 a).

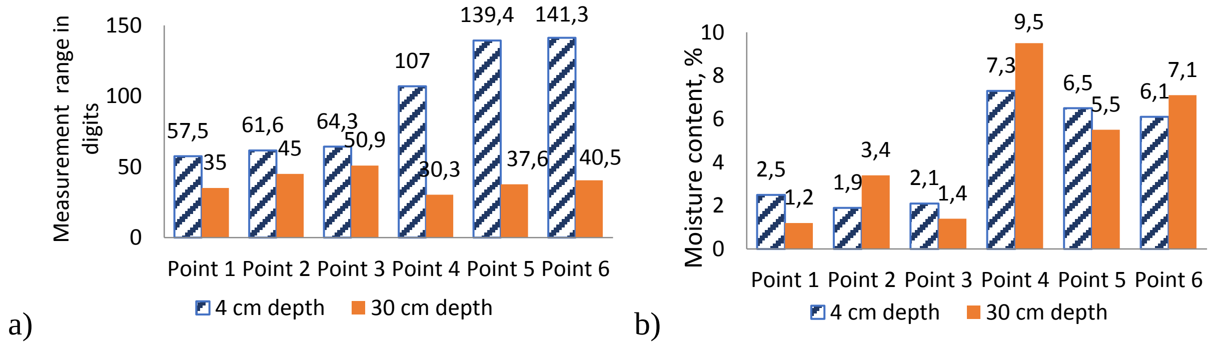


Fig. 2.3. Moisture measurements in Case building 1: a) non-destructive measurements with Trotec T600 and Trotec T650; b) destructive moisture content measurements.

Comparing the results of 40 mm depth, it appears that the trend remains the same – moisture content in the first three points is two, three times lower than near the ground (measurement points 4, 5, and 6). Situation with the results of 300 mm depth are different, there is no correlation between the results of non-destructive and destructive methods. It could be explained using a drill for the sampling. The drill temperature during drilling exceeds 150 °C, which is enough to remove part of the moisture of the brick dust even before drying it in the oven.

Parameters of Historic Construction Material

Test results of historic bricks showed large diversity in their determined properties. For example, average density values of batch of historic brick are in the range of 1.51–1.93 g/mL (Fig. 2.4 a). The values of mass water absorption range between 8.6–22.9 % on average and show an inverse trend to that of density (Fig. 2.4 b). This can be explained by the close relationship between water absorption and open porosity which has an impact on density.

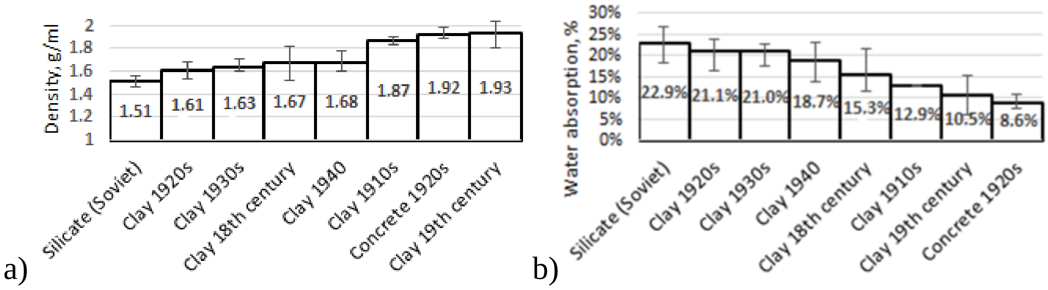


Fig. 2.4. Laboratory test results: a) dry density; b) water absorption.

Even the samples obtained from the same building show large result variation – compressive strength of four samples, all taken from one building, varied between 10.4 MPa and 23.4 MPa.

Brick samples with volumetric water absorption less than 20 % did not show any damage after 15 cycles of freezing and thawing except for two specimens in which cracks appeared after the tenth cycle. But the most significant part of brick samples with volumetric water absorption higher than 36 % was broken entirely or with large cracks after the second to the sixth cycle of freezing and thawing. Old silicate bricks started to crack after the first cycle, and after eight cycles all of the silicate bricks had broken apart, consequently, it can be assumed that they are susceptible to frost damages, that is also mentioned in other studies.

The test results are presented in Fig. 2.5 a. Fully saturated samples split or formed critical cracks between 2 to 6 freezing-thawing cycles. Samples saturated to 20 % of total volume have no visible damage after 15 freezing-thawing cycles.

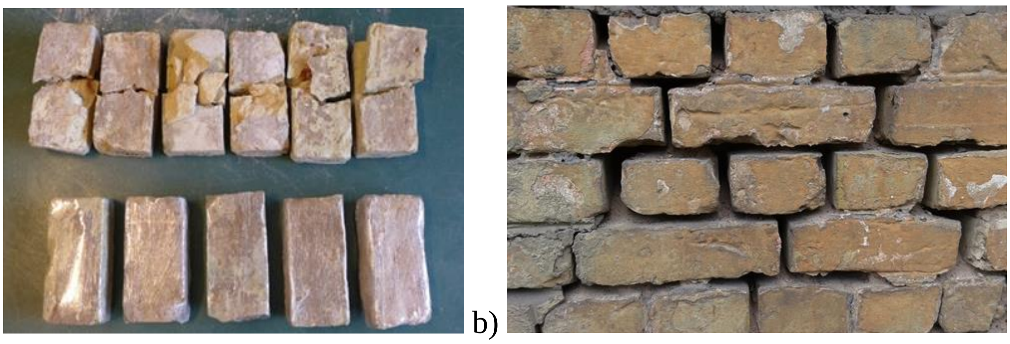
a)  b)

Fig. 2.5. a) Bricks after 15 frost-thaw test cycles: fully saturated samples (~36 %) in upper row, while samples saturated to 20 % in bottom row; b) extensive loss of mortar due to high presence of sulphates.

Three soluble salts – nitrates, chlorides and sulphates were detected in more than half of the tested brick samples. The presence of nitrates is usually associated with infiltration of sewage water or the proximity of burial sites, while sulphates are often present because of atmospheric pollution particularly in urban areas. All particular buildings are located in old parts of Riga, close to markets or the Daugava river, i.e. in places with high groundwater level and high pollution level.

The highest level of sulphates was detected in the sample taken from a building which, according to non-destructive moisture measurements, had the highest moisture level compared to other examined buildings. In the same brick sample, the presence of nitrates and chlorides was detected. These findings confirm what was mentioned in the studies of other researcers – sulphates usually attack mortar in masonry (Fig. 2.5 b). Any further mortar loss will create the risk of local collapse of the brickwork.

Dolomite samples from Case building 2 were obtained and tested in the laboratory to determine their main properties – density, specific heat capacity, thermal conductivity, total porosity, capillary saturation, water vapour resistance factor, water uptake coefficient and moisture storage needed for hygrothermal simulation. The results are presented in Tables 2.1 and 2.2. Afterwards, these values were used as input data to characterize the material properties in simulation program DELPHIN 6.

Table 2.1

Determined Properties of Dolomite

Name of the material property	Symbol (Unit)	Mean value	Standard deviation	Min. value	Max. value
Bulk density	ρ_b (kg/m^3)	2346.5	447.8	1696.8	2949.5
Open porosity	Θ_{por} (m^3/m^3)	0.1602	0.0224	0.1299	0.2008
Thermal conductivity	λ_{dry} (W/mK)	2.0478	0.0108	2.0362	2.0574
Heat storage capacity	c (J/(kg K))	779.2842	5.1457	774.3023	784.5794
Dry-cup vapour diffusion	μ_{dry} (–)	44.14	29.18	26.67	77.83
Wet-cup vapour diffusion	μ_{wet} (–)	2113.88	943.36	1192.82	3078.06
Water uptake coefficient	A_w (kg/m$^2\sqrt{s}$)	0.0599	0.0110	0.0477	0.0691
Capillary saturation moisture content	Θ_{cap} (m^3/m^3)	0.1079			

Table 2.2

Sorption Moisture Content

φ, %	t, °C	$\Theta_l(\varphi)$, m^3/m^3			
		Mean value	Standard deviation	Min. value	Max. value
84.7	23	0.009 524	0.000 570	0.008 907	0.010 26
53.5	23	0.004 830	0.000 284	0.004 553	0.005 14
32.9	23	0.001 787	0.003 670	0.000 000	0.009 26

Laboratory Study of Internally Insulated Wall

First test results showed that the relative humidity growth rate is high during the first five days for all materials and is slowing down when approaching equilibrium conditions. Temperature for all samples is reaching equilibrium in the first five days.

Relative humidity between masonry and the wood fibre (Fig. 2.6) is higher when the vapour barrier is not applied and reaches 80 % (test 2), while, if the vapour barrier is installed, relative humidity increases up to 74 % (test 1). Without the vapour barrier the growth rate of relative humidity is higher as well. The initial temperatures are different for both tests, but they stabilize after five days.

Mineral wool with two different vapour barrier types and EPS shows the same trend of behaviour of relative humidity as wood fibre. The growth rate of relative humidity is very high during the first two days and stabilizes after that, reaching 83.5 % in the case of mineral wool (in both tests) and 80 % in the case of EPS (in both tests). When the vapour barrier is applied to granular aerogel, the relative humidity increases very quickly during the first two days and increases up to 79 % during the next 20 days. If aerogel is used without the vapour barrier, relative humidity is lower (74 %).

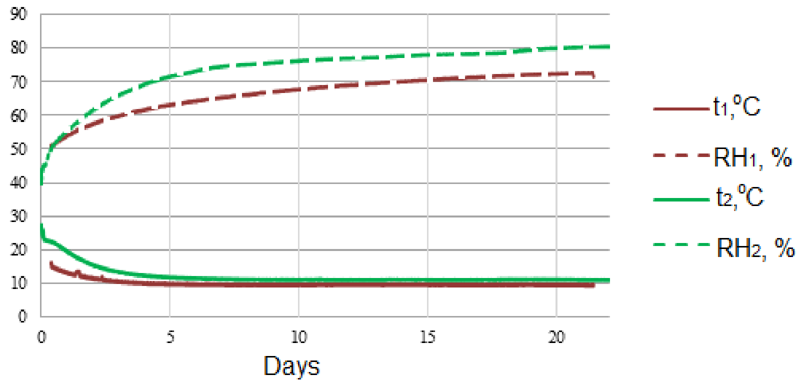


Fig. 2.6. Measured temperature and relative humidity between masonry and wood fibre: t_1, RH_1 – without vapour barrier; t_2, RH_2 – with vapour barrier.

Mould growth is one of the significant risks associated with internal insulation, as the hygrothermal conditions are favourable for spore germination and further mycelium growth. Suppose the temperature is +10 °C and there are enough nutrients and time, spore germination and mycelium growth start at 76 % relative humidity. In both test rounds, temperature stabilized around +10 °C and relative humidity was above 76 % for all insulation materials. When the test wall was opened on the 22nd day after the beginning of the test, mould was discovered on one of the corners of the wood fibre mat. Figure 2.7 illustrates the wood fibre affected by mould and magnified material with and without mould on it. After the second test round, mould was also discovered in the middle of the insulation material. On the rest of the insulation materials, mould was not discovered.

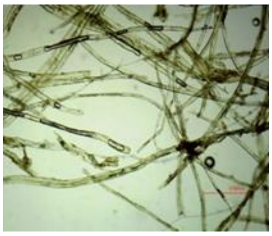
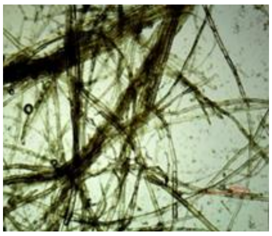
a)  b)  c) 

Fig. 2.7. Mould on wood fibre mat after the test: a) mould on the top right corner; b) magnified wood fibre without mould; c) with mould.

Both by DELPHIN simulated relative humidity and temperature changes at a slow rate asymptotically approaching equilibrium conditions only on the 14th day for mineral wool, on the 17th day for EPS and on the 21st day for wood fibre. All three samples stabilize at different temperatures: 11.55 °C for wood fibre, 10.44 °C for EPS and 10.37 °C for mineral wool. The equilibrium relative humidity also differs and is 39.1 % for mineral wool, 43.9 % for EPS and 71.4 % for wood fibre. The results for wood fibre are given in Fig. 2.9 – temperature (pre sim), relative humidity (pre sim).

Correlation analysis shows that satisfactory results are reached for temperature as correlation coefficient R^2 is in the range of 0.81 (EPS) to 0.86 (wood fibre). Correlation is good for simulated and measured results for relative humidity of wood fibre (R^2 = 0.84), but good correlation is not reached for relative humidity for EPS (R^2 = 0.59) and mineral wool (R^2 = 0.54). The correlation analysis example for wood fibre is given in Fig. 2.8.

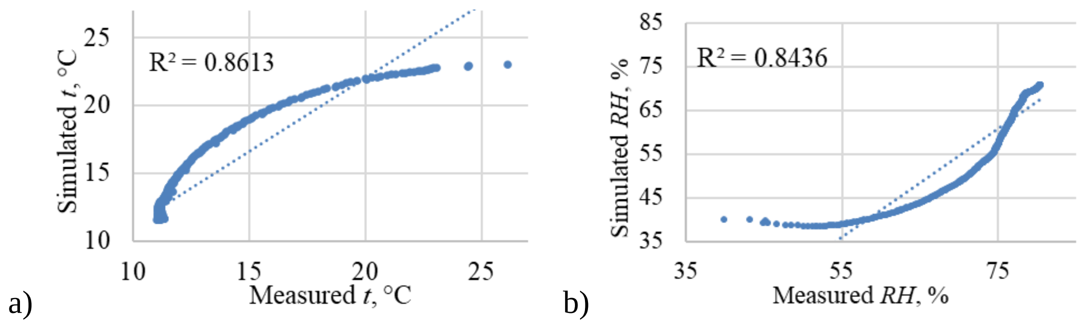


Fig. 2.8. Correlation between simulated and measured data for wood fibre:
a) temperature; b) relative humidity.

The model fitting to measured data was improved by applying the parametric analysis. It was carried out by modifying the parameters of masonry, mortar and insulation materials. Thermal conductivity, density of dry material, and water vapour diffusion resistance factor for insulation materials were changed to values supplied by material producers. For bricks and mortar thermal conductivity, specific heat capacity, liquid water conductivity at effective saturation, water uptake coefficient and initial relative humidity were adjusted.

Figure 2.9 illustrates the changes of temperature and relative humidity during simulation before and after the experiment and measured results in masonry with wood fibre without vapour barrier. The central gap between measured and pre-test simulation temperatures is observed during the first 10 days when the pre-test simulation temperature is decreasing at a slower rate than measured temperature. The post-test simulation results fit well with measured temperatures. The temperature at the equilibrium differs only by 0.6 °C.

The same tendency is observed for the relative humidity: the pre-test simulation has a much lower increase rate at the beginning, hence it has not reached equilibrium during the simulation period. The post-test simulation and measured relative humidity fit well and both are stabilizing at around 80 %.

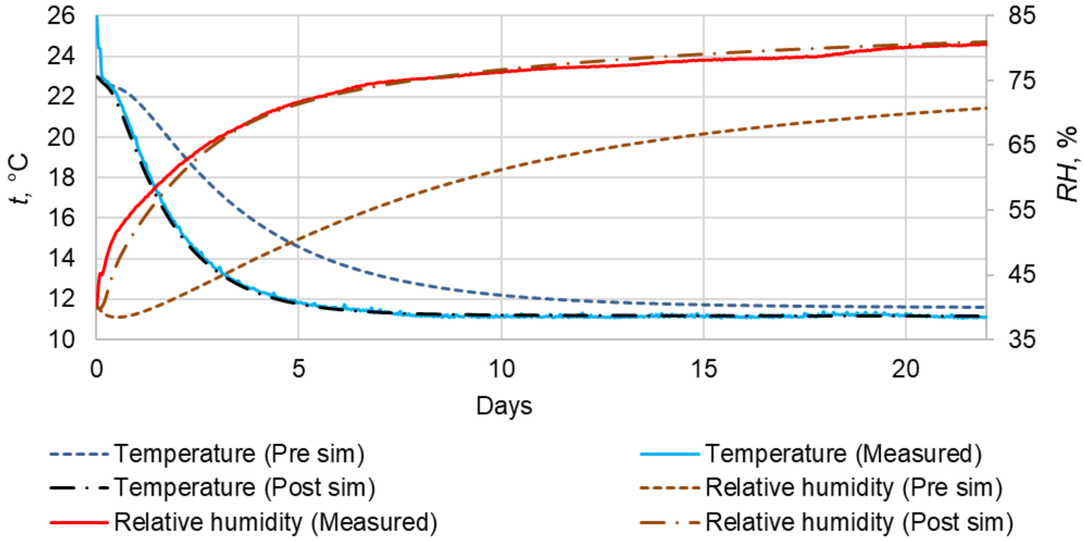


Fig. 2.9. Behaviour of temperature and relative humidity between masonry and wood fibre without vapour barrier insulation layer: simulation before and after the experiment, and measured results.

2.2. Energy Consumption

Prior to a more in-depth feasibility study and in-situ measurements, calculations and dynamic simulation were performed to determine the potential for heat savings of case buildings. The results of total heat demand for case buildings are shown in Tables 2.3–2.5. Scenarios 2 and 3 are compared to the performance of the building as it had been initially constructed (Scenario 1).

Table 2.3

Calculated Energy Demand in Case Building 1

	Total, kWh	Per heated area, kWh/m^2	Per facade area, kWh/m^2	Savings, %
Scenario 1	36 569.73	564.35	239.64	–
Scenario 2	24 867.57	383.76	162.96	32
Scenario 3	8030.08	123.92	52.62	78

Energy in Case building 1 is consumed by heating, lighting, ventilation, heat pump and hot water. The analysis of energy consumption from the energy bills provided by owner showed that energy consumption has greatly varied during October 2014 and May 2017. Annual energy consumption was in 2015 – 160 kWh/m^2 and in 2016 – 235 kWh/m^2. There might be several reasons for the differences: variations in outdoor climate, hot water consumption by the public restroom, heat pump efficiency and air supply volumes by the ventilation unit caused by the lack of energy management.

Table 2.4

Simulated Energy Demand in Case Building 2

	Total, kWh	Per heated area, kWh/m^2	Per facade area, kWh/m^2	Savings, %
Scenario 1	66 071	194.42	240.48	–
Scenario 2	42 753	125.80	155.61	35
Scenario 3	18 334	53.95	66.73	72

According to the estimations of the owner of Case building 2, around 30 m^3 firewood dried for 2 years were used in the 2017/2018 heating season. Assuming that the moisture content of the firewood is 20 %, and 40 kW burner's efficiency is η = 75 %, and subtracting energy for hot water preparation, calculated annual energy consumption per heated area is 86.50 kWh/m^2. That is more than calculated in the third scenario (53.95 kWh/m^2). The difference can be caused by a number of reasons: 1) poor quality of construction works, thermal bridges; 2) measured room temperatures (+20 °C ... +22 °C) are higher than calculated (+18 °C ... +20 °C); 3) heat gains do not corresponds to the schedule made in calculation model; 4) relative humidity in the rooms is lower (average 35–40 % in the heating season) than assumed in the model (50 %); 5) climatic data entered in the model do not correspond to actual climate; 6) the wood moisture is higher than assumed; 7) the efficiency of boiler is lower than assumed. Also, the used software may not adequately capture the physical phenomena of interest in historic buildings. Other researchers have pointed out the issue about the result diversity when using different building simulation programs to simulate energy consumption or hygrothermal performance of historic buildings. Notably the heat flux measurements that later were performed in the case study building showed that heat transfer coefficient of the living room wall is 0.21 W/(m^{2}K), which corresponds to the values entered into the TRNSYS model 0.208–0.2115 W/(m^{2}K).

Table 2.5

Simulated Energy Demand in Case Building 3

	Total, kWh	Per heated area, kWh/m^2	Per facade area, kWh/m^2	Savings, %
Scenario 1	413 660	171.6	175.4	–
Scenario 2	377 490	156.61	160.1	8.7
Scenario 3	232 490	96.5	98.6	43.8

Unfortunately, Case building 3 was not heated during the period of research, therefore the actual energy consumption is not known.

2.3. Hygrothermal Performance of Internally Insulated Construction

The hygrothermal conditions in internally insulated external walls were monitored in-situ in all three case buildings. Additionally, hygrothermal simulation was made to validate the reliability of predictions of hygrothermal conditions and moisture related risks in internally insulated historic buildings.

In-situ Measurements

Figures 2.10 and 2.11 represent temperature measurements in Case building 1. Temperature measurements during winter (Fig. 2.10) show that indoor temperature is very steady and does not vary too much depending on the outdoor temperature. Temperature in the layers between the wall and VIP and between the wall and aerogel drops below 0 °C, when outdoor temperature drops below –9 °C and below –11 °C, respectively. The lowest temperature registered between the wall and VIP is –9.32 °C, between the wall and aerogel – 7.08 °C.

Figures 2.10 and 2.11 also show temperatures at the borders between insulation material and plasterboard, between insulation material and masonry wall and in the middle of insulation material. Temperatures in the middle of insulation material – aerogel and vacuum insulation panel, are very close. However, on both sides of insulation materials temperatures differ depending on the material applied. Both materials are 50 mm thick but with different thermal conductivity values thus leading to average 2.2 °C higher temperatures between masonry and aerogel in the coldest days compared to VIP. Temperatures at the plasterboard and insulation material border show opposite values for both materials, where VIP shows up to 3 °C higher temperature than aerogel.

Temperature distribution in summer is presented in Fig. 2.11. The results indicate the potential problems of indoor air overheating during summer. The indoor air temperature and temperature between insulation layers is about 6 °C higher than the outdoor air temperature. Temperature measurements show that the thermal inertia of the brick wall cannot be effectively used to regulate indoor air temperature during summer.

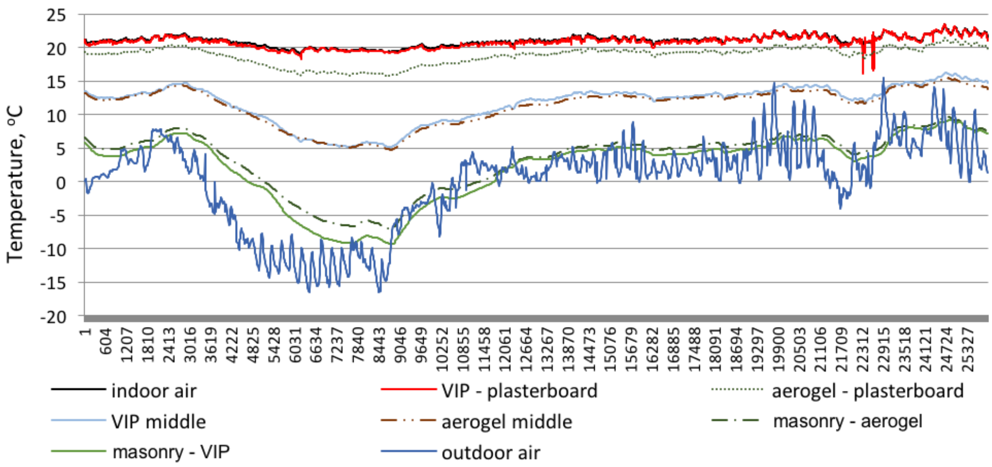


Fig. 2.10. Case building 1. Temperatures in winter (1 January to 31 March). *x*-axis represents the time step (5 min).

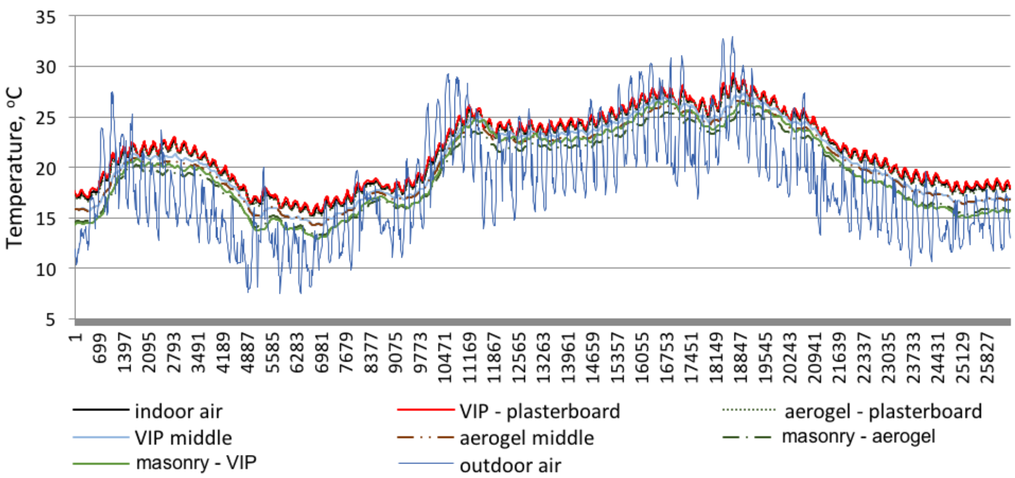


Fig. 2.11. Case building 1. Temperatures in summer (1 June to 31 August).
x-axis represents the time step (5 min).

Figure 2.12 shows the temperature distribution in the wall construction with the lowest outdoor temperature. The whole brick wall and part of the insulation are at temperatures below 0 °C, which is considerably under the freezing temperature.

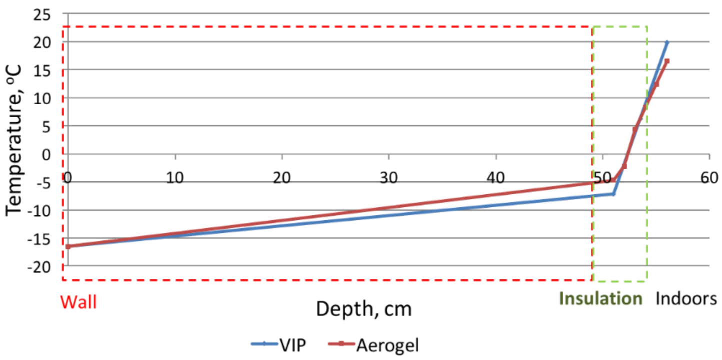


Fig. 2.12. Measured temperature distribution in the wall construction
at the lowest outside temperature (–16.5 °C).

The freezing depth up to 30 cm was reached for around 100 hours during the 11-month period of measurement. The analysis shows that for internally insulted walls the outdoor air temperature under –5 °C means that the whole existing wall will be subjected to frost damage risk. However, the fact that whole wall temperature is lower than the freezing point of water does not automatically mean that frost damage will occur. Risks related to frost damage could occur only if the moisture content in the materials of the wall would be higher than its capillary saturation.

The measurements in Case building 2 show that the relative humidity rarely exceeds critical 80 % at the wall interfaces. Exception is 8 March 2018, when the water leakage from water supply system was detected on the first floor. RH between insulation and vapour barrier rapidly rises from 25 % to 60 % and then slowly decreases within the next two weeks. At the exact moment RH between the dolomite wall and insulation layer (Fig. 2.13) rapidly rises to 100 % and then slowly dries out during spring and summer.

The measured temperatures (Fig. 2.14) between the living room wall layers follow the outside temperature fluctuations.

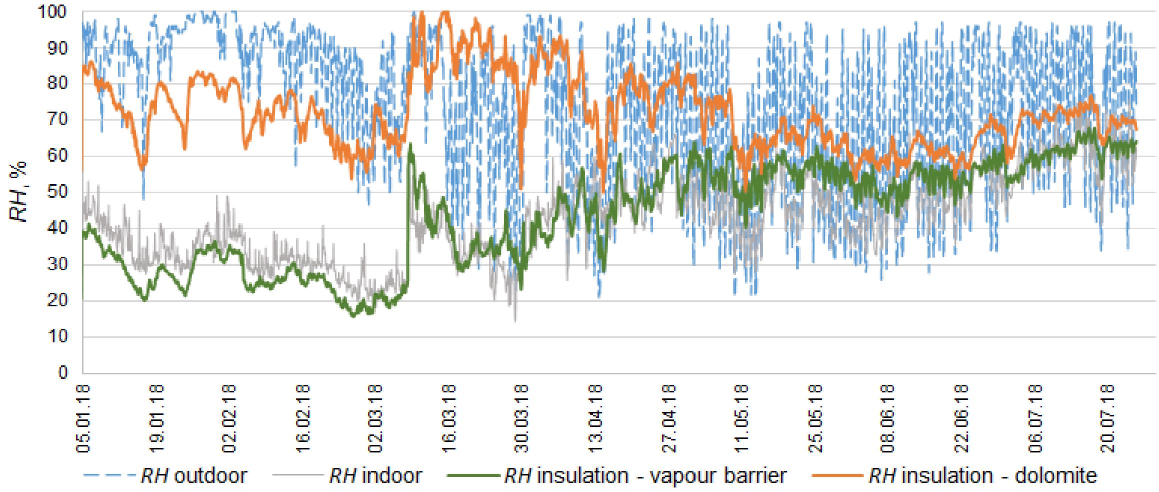


Fig. 2.13. Case building 2. Measured relative humidity at the interfaces of the living room wall.

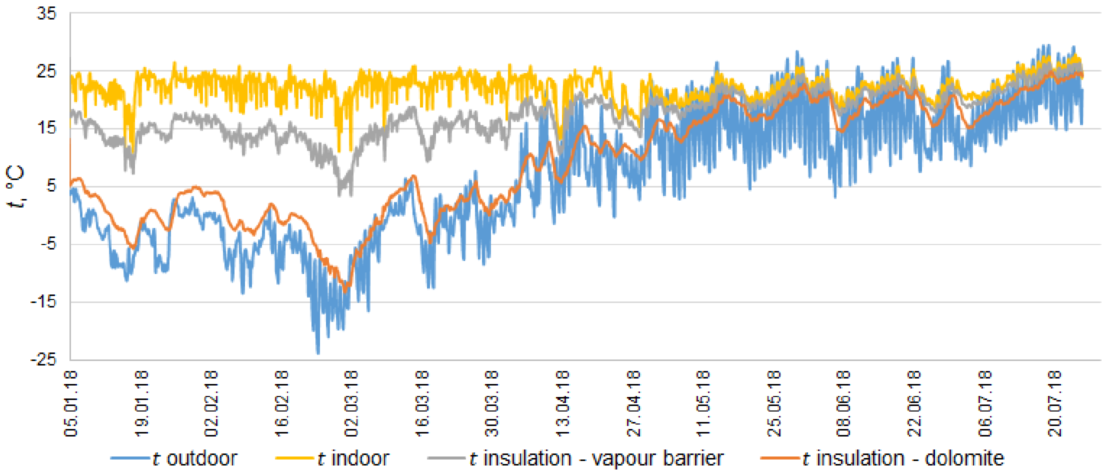


Fig. 2.14. Case building 2. Measured temperature at the interfaces of the living room wall.

The measured relative humidity in the bathroom wall is shown in Fig. 2.15. Average relative humidity between dolomite and insulation with few exceptions stays below 80 % during autumn, winter and spring, and below 70 % during summer. The measured temperatures between dolomite and insulation (Fig. 2.16) follow the outside temperature during the heating season and is between the outdoor and indoor temperature during the off-heating season.

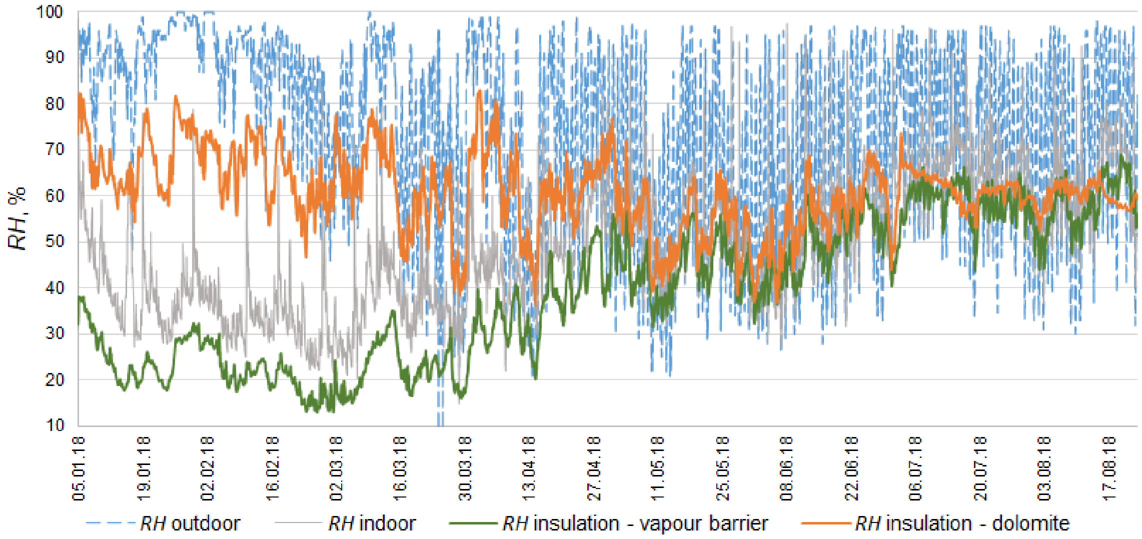


Fig. 2.15. Case building 2. Measured relative humidity at the interfaces of the bathroom wall.

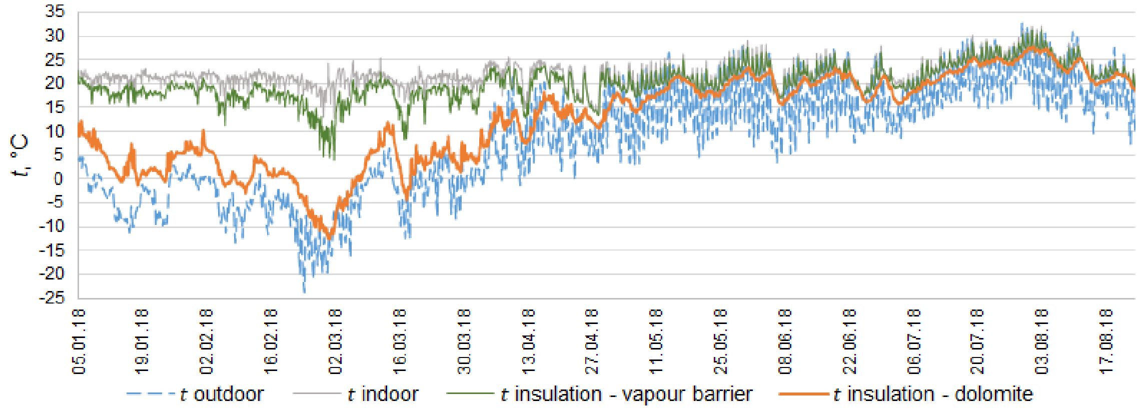


Fig. 2.16. Case building 2. Measured temperature at the interfaces of the bathroom wall.

For Case building 3, Fig. 2.17 represents temperatures in the wall on the 1st floor. Difference between temperatures on both sides of the insulation is approximately 5 °C during winter. Temperature measurements in the walls of Case building 3 follow the outdoors readings. Spring and summer measurements show that added insulation layer does not prevent overheating of the building.

Figure 2.18 represents measurements of the relative humidity in the wall construction layers on the 1st floor. Relative humidity between masonry and insulation stays below 80 % and between insulation and plasterboard below 60 %, the same as in the room. The same results showed the wall on the 2nd floor.

Heat flux density and temperature measurement data were used to determine the measured heat transfer coefficient in the walls of Case building 1, that were insulated with aerogel and VIP, and in the walls of Case building 2, insulated with 150 mm and 200 mm of mineral wool.

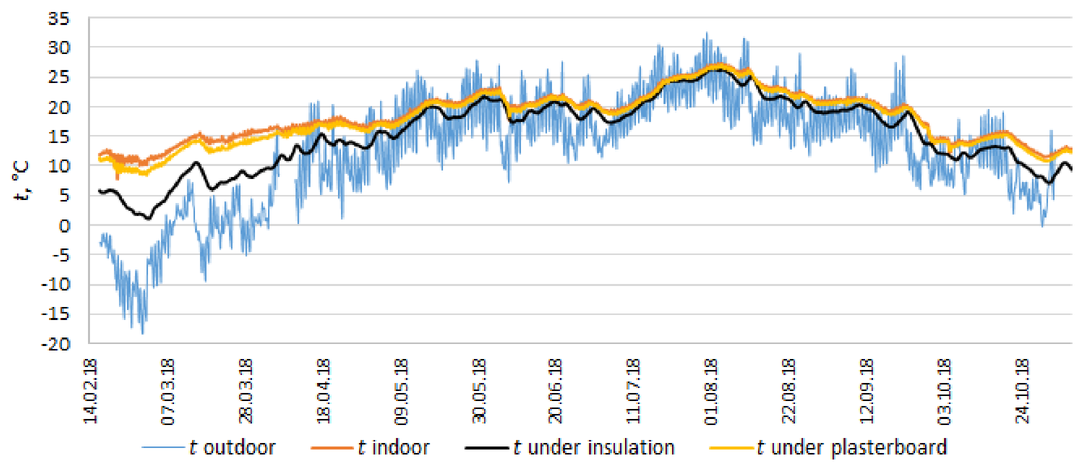


Fig. 2.17. Case building 3. Temperature measurements of the wall on the 1st floor.

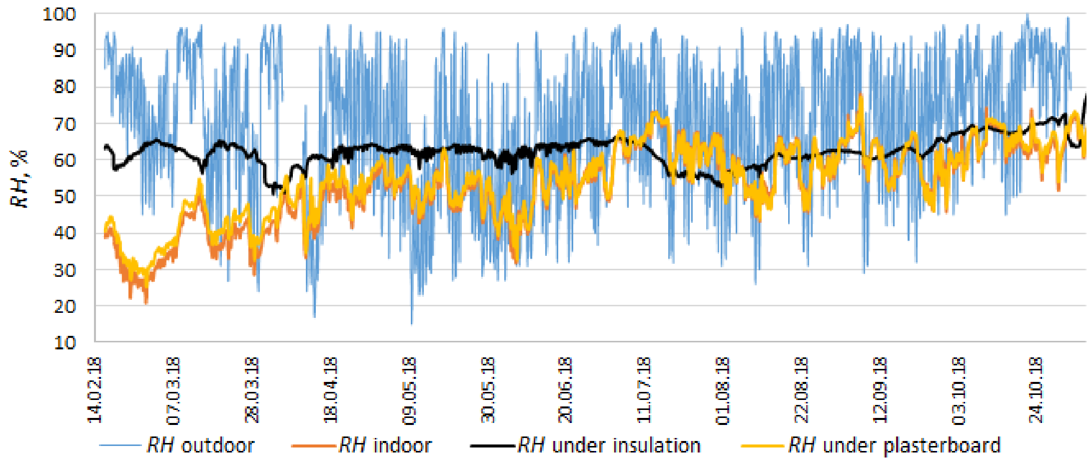


Fig. 2.18. Case building 3. Relative humidity measurements of the wall on the 1st floor.

It is possible to calculate heat transfer coefficient by using standard values of heat conductivity of insulation and the thickness of it. The calculated heat transfer coefficient of the wall insulated with aerogel is 0.267 W/(m^{2}K), but for wall insulated with VIP it is 0.093 W/(m^{2}K). However, the average measured heat transfer coefficient of the wall insulated with aerogel is 0.273 W/(m^{2}K) but with VIP 0.060 W/(m^{2}K). The measurement showed that the heat transfer of aerogel is almost the same as calculated, but for the VIP considerably lower than calculated. Other researches show that the heat conductivity of the VIP can be smaller in the middle of the insulation panel and more prominent around the borders of the VIP. Also, the heat conductivity of VIP is lower at lower temperatures (around 0.0042 W/(m·K) at 0 °C).

In Case building 2, the measured heat transfer coefficients are 0.21 W/(m^{2}K) for the living room wall (150 mm mineral wool) and 0.19 W/(m^{2}K) for the bathroom wall (200 mm).

Water content measurements in the walls of Case building 2 are shown in Fig. 2.19. As described previously, the sampled building's dolomite stones have a density from 1696.8 kg/m^3 to 2949.5 kg/m^3, and the average water content per volume is 13 % (10–17 %), determined by immersion in water. Monitoring results show that water content mostly stays below 2 % in both measurement points, so it does not reach its saturation. In Fig. 2.19, rainfall is added as a reference to fluctuations.

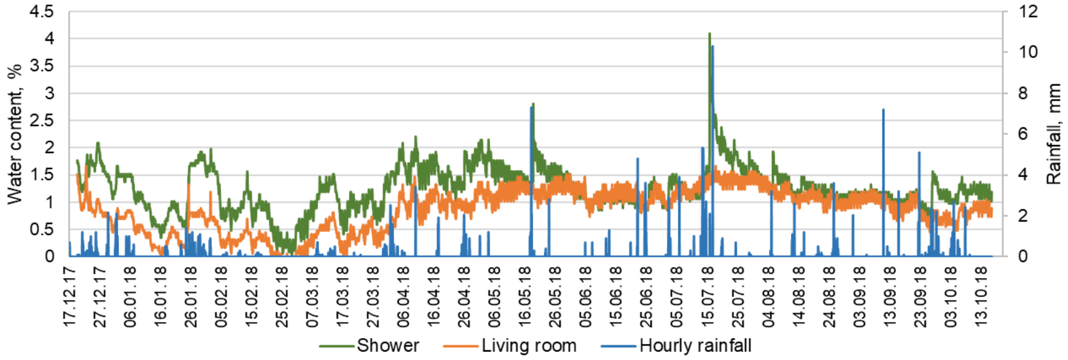
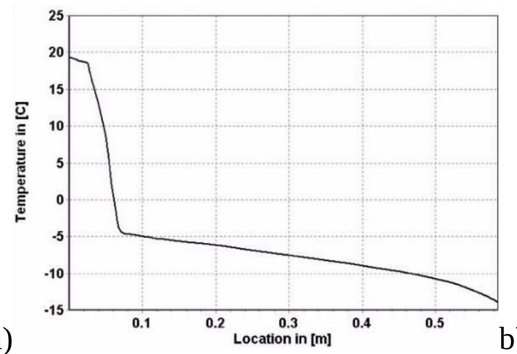


Fig. 2.19. Case building 2. Results of water content measurements.

Hygrothermal Simulations

Figure 2.20 illustrates simulation results for temperature distribution in the wall of Case building 1 in the coldest day (measured outside temperature on 23 January at 9 a.m. was –16.55 °C, while the simulation used outside temperature –15.7 °C, which was registered in Riga on 23 January, 2014 at 9 a.m.). The tendency is similar to the measured data presented in Fig. 2.12 for both insulation materials.

a) 

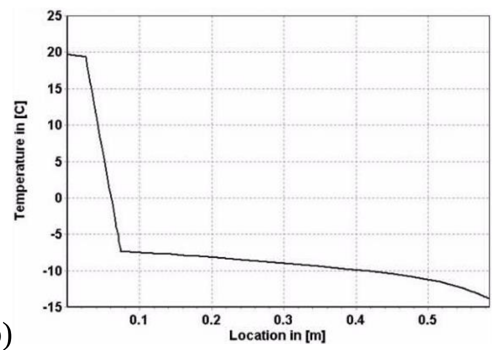
b) 

Fig. 2.20. Case building 1. Simulated temperature distribution (23 January at 9 a.m.) in the wall insulated with a) aerogel; b) VIP (outdoor on the right and indoor on the left of both graphs).

When simulating relative humidity distribution in the wall, the assumption was made that masonry does not get wet of rain because of the paint applied to the surface, but water vapour movement is not disturbed. Figure 2.21 shows relative humidity distribution in the wall insulated with both insulation materials in the coldest day of the year (23 January at 9 a.m.). It presents the simulation results for the wall painted with water repellent hydrophobic paint (as it is in the case study building) and without it.

In both walls without water repellent hydrophobic paint (Fig. 2.21 b and d), changes of relative humidity take place within the last 10 cm to 12 cm, where during spring (March to May) relative humidity is constantly over 90 %, during summer masonry dries slightly, RH staying around 90 %, but in autumn and winter, the level of it in the masonry increases and continuously remains over 90 %. Active wetting reaching 100 % and drying occurs only within the last 2 cm to 4 cm of masonry. This might lead to severe frost damages if capillary saturation is reached. High relative humidity can also promote salt crystallization in masonry. For the painted walls, the situation is much different with relative humidity increasing to a maximum of 90 % within the last 6 cm of the masonry during spring and summer, but during autumn and winter, relative humidity increases on the outer side of the wall and exceeds the maximum 95 % within the last 2 cm of the masonry.

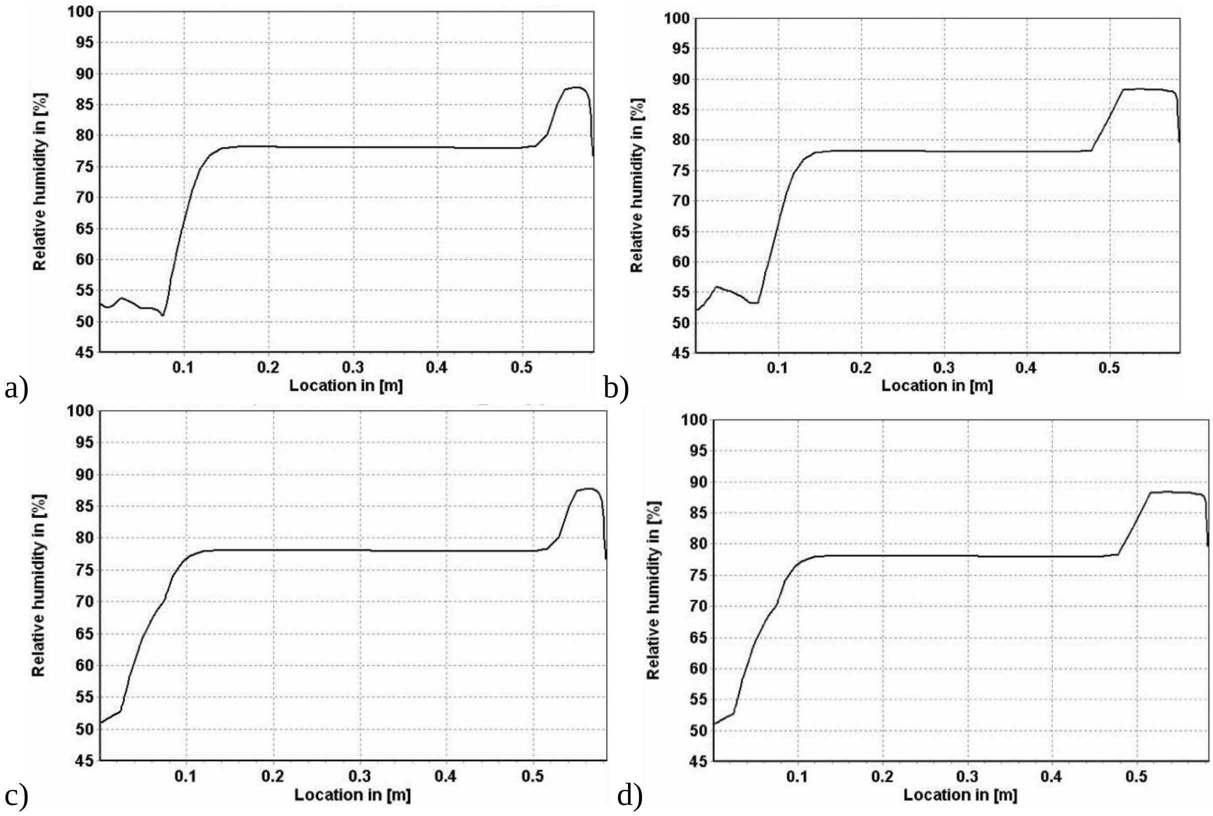


Fig. 2.21. Case building 1. Simulated *RH* in the wall (23 January at 9 a.m.) insulated with: a) aerogel and water repellent hydrophobic paint; b) aerogel and without paint; c) VIP and water repellent hydrophobic paint; d) VIP and without paint; (outdoor on the right and indoor on the left of both graphs).

Taken together, our findings in Case building 1 demonstrate that the calcium silicate masonry part of the internally insulated wall in cold climate lead to exposure to freeze-thaw damages if the moisture content of the brick is higher than the capillary saturation. This process strongly depends on unfavourable outdoor conditions for wall types with and without water repellent hydrophobic paint.

Simulated relative humidity and temperature in the bathroom wall of Case building 2 are shown in Figs. 2.22 and 2.23, respectively. Measurement results are added for comparison. Simulated relative humidity between the insulation and vapour barrier (Fig. 2.22) follows the trend of the indoor relative humidity, although it is 5 % to 10 % lower than the measured level during the heating season (relative humidity sensors accuracy ±3.5 %).

Simulated temperatures between the insulation and vapour barrier (Fig. 2.23) and between dolomite and insulation (Fig. 2.25) closely follow indoor temperature and outdoor temperature, respectively. Differences between simulated and measured temperatures under the plasterboard are caused by the room temperature sensor's placement – off of the wall.

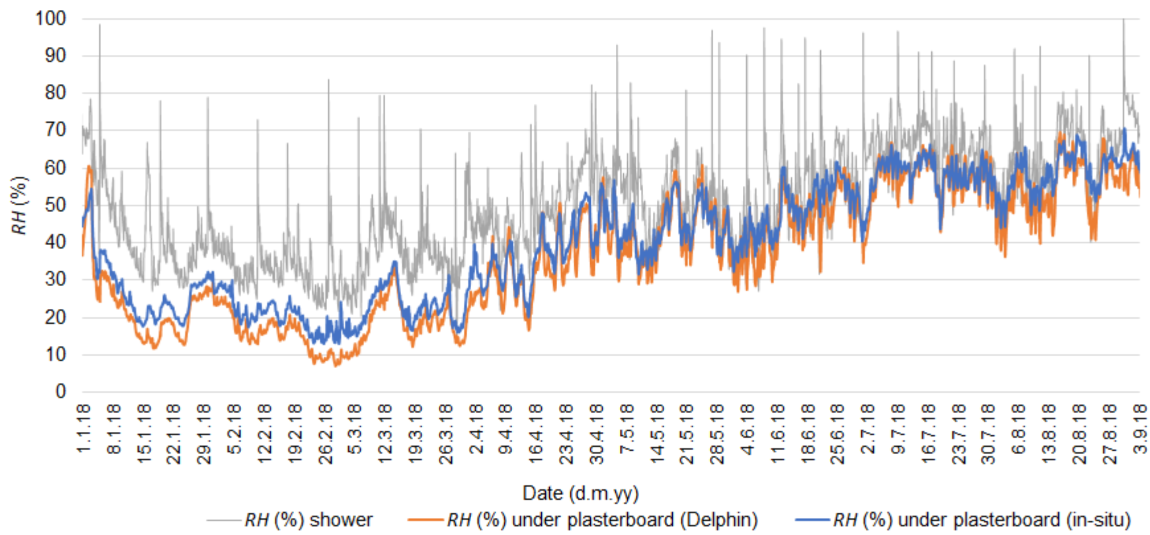


Fig. 2.22. Case building 2. Relative humidity of the bathroom wall between insulation and vapour barrier.

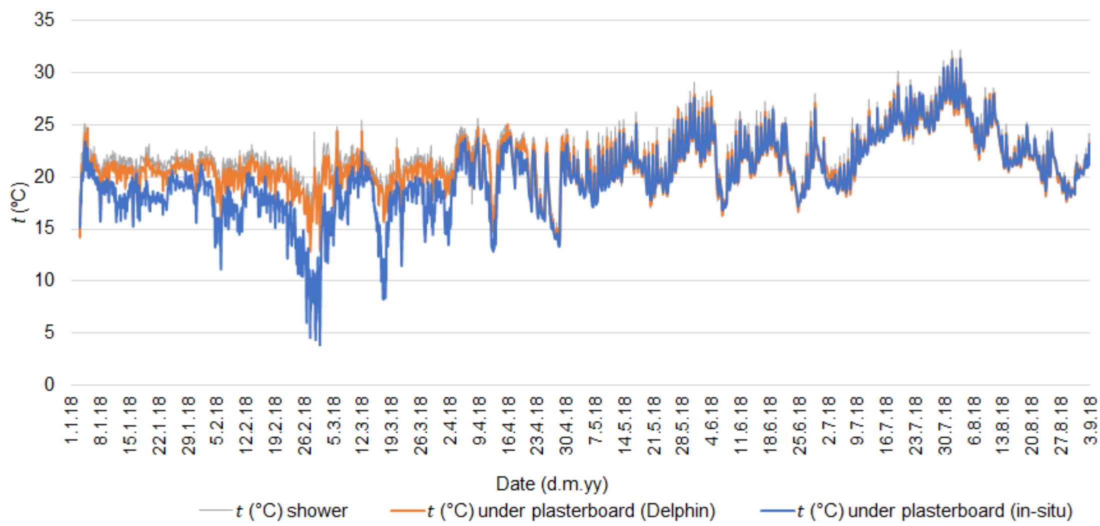


Fig. 2.23. Case building 2. Temperature of the bathroom wall between insulation and vapour barrier.

The simulated and measured relative humidity between thermal insulation and dolomite for the bathroom wall is shown in Fig. 2.24. During the heating season simulated relative humidity is slightly higher than that obtained during the measurements, sometimes even reaching the 90 % mark. However, in the case of living room, the simulated and measured results showed a better match. One of the possible reasons for the inconsistency is the heterogeneity of dolomite properties, which is proved by laboratory tests of dolomite samples, for example, the density ranges from 1696.8 kg/m^3 to 2949.5 kg/m^3, the range of vapor diffusion coefficients is from 26.67 to 77.83. Besides, in this kind of simulations, it always should be kept in mind that materials, especially historical ones, are inhomogeneous and anisotropic. However, software assumes that each building and insulation material behaves as a collection of identical infinitesimally small representative elementary volumes. Thus, there are differences between the assemblies as built and as modelled. Their geometry as built, including joints, cracks, voids, leaks and air spaces, is never fully known, which is why models consider idealized sections.

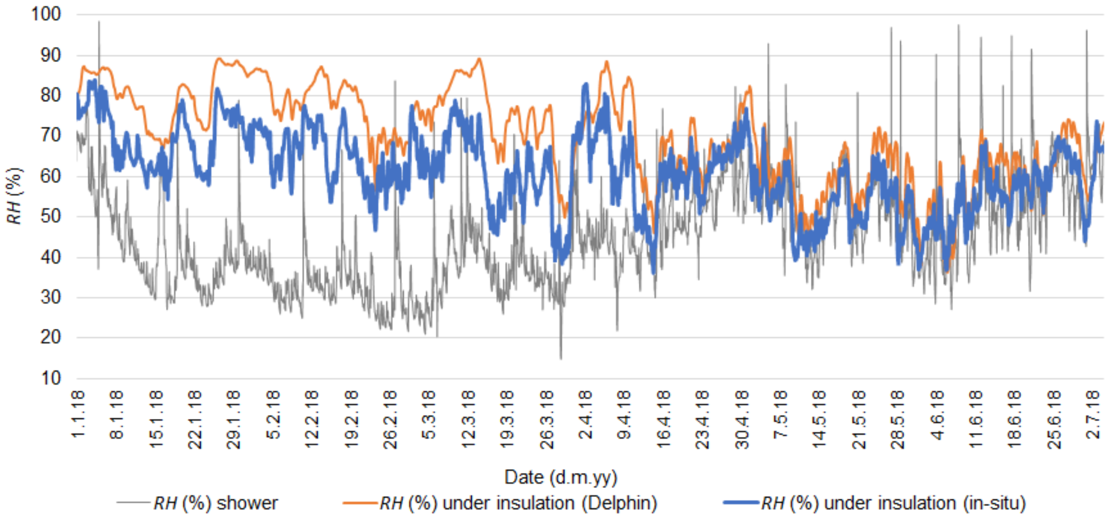


Fig. 2.24. Case building 2. Relative humidity of the bathroom wall between dolomite and insulation layers.

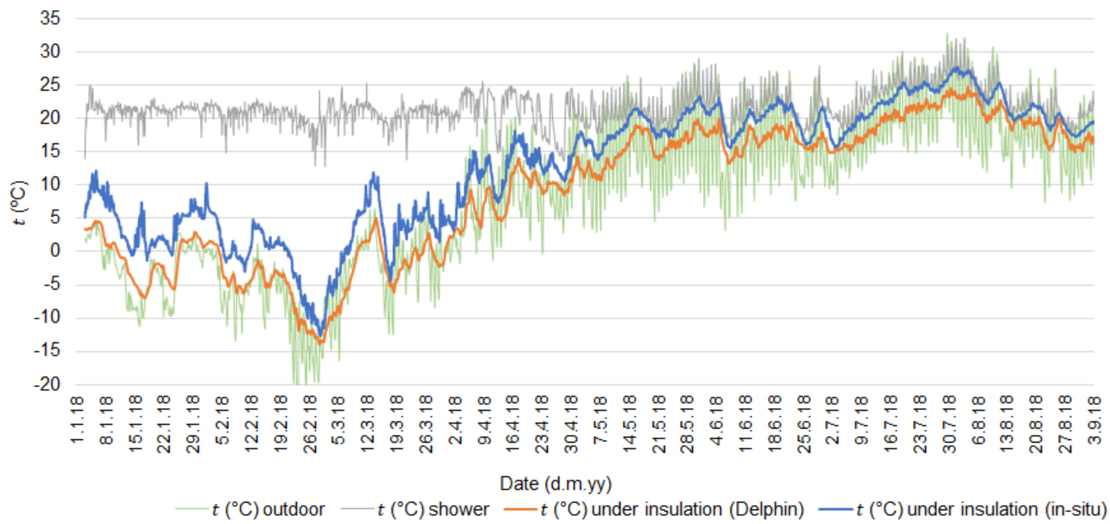


Fig. 2.25. Case building 2. The temperature of the bathroom wall between dolomite and insulation layers.

As described previously, simulated relative humidity level in the walls of Case building 2 is higher than measured during the g heating season, which means that DELPHIN gives results on the safe side. The same refers to a simulated temperature between dolomite and insulation, as in both cases the simulated temperature is lower than the measured, though the simulation results show a consistent trend with measured results. The temperature correlation between dolomite and insulation (*t* under insulation) in both walls is extremely strong, $R^2 = 0.9789$ in the living room and $R^2 = 0.9778$ in the bathroom (Fig. 2.26 b). But between insulation and plasterboard correlations it is considerably lower: $R^2 = 0.4003$ in the living room and $R^2 = 0.7876$ in the bathroom (Fig. 2.26 d). These low correlations are caused by the placement of the indoor temperature sensor, as the indoor temperature is a primary variable that influences the temperature under plasterboard in the simulated model. Indoor temperature sensors were placed away from the exterior wall, thus measured higher temperature, not the one that is on the surface of the wall.

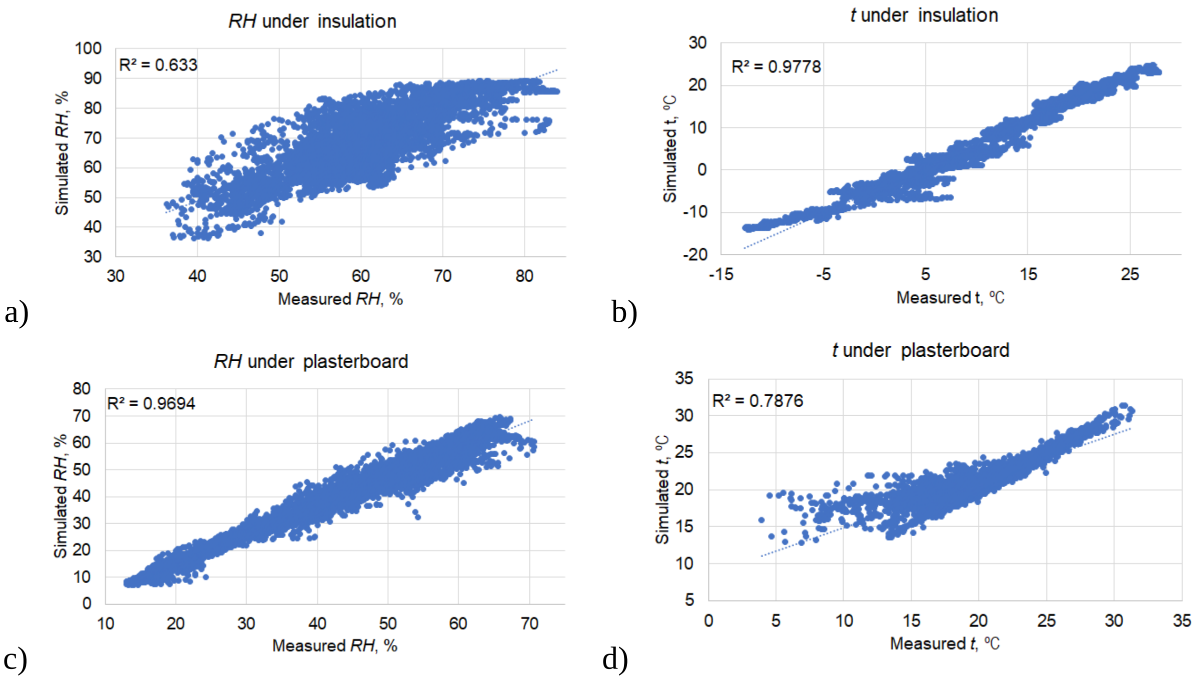


Fig. 2.26. Correlation between simulated and measured data in the bathroom wall: a) relative humidity between dolomite and insulation; b) temperature between dolomite and insulation; c) relative humidity between insulation and plasterboard; d) temperature between insulation and plasterboard.

The correlation of simulated and measured relative humidity between dolomite and insulation is low: $R^2 = 0.4775$ in the living room and $R^2 = 0.633$ in the bathroom (Fig. 2.26 a). In the case of relative humidity between insulation and plasterboard, a correlation between measured and simulated data is very strong: $R^2 = 0.9047$ in the living room and $R^2 = 0.9694$ in the bathroom (Fig. 2.26 c).

The correlation analysis in Case building 2 does not include possible deviation of measurement accuracy. Furthermore, outside temperature and relative humidity data are taken from weather station Skrīveri, which is located 20 km away from the case study building, therefore not corresponding exactly to the conditions at Case building 2.

Nevertheless, the results of hygrothermal modelling validate the reliability of prediction of hygrothermal conditions and risk of mould growth and frost damage in internally insulated historic buildings.

CONCLUSIONS

Achieving climate and energy goals is not possible without deep retrofit of existing buildings. However, improvement of energy efficiency in the historic building sector with cultural heritage is a complex problem combination, as the decision involves many different factors that should be taken into consideration. In most cases, to preserve the cultural and historical value, the only solution is external wall insulation form the inside. But at the same time, wall insulation from the inside poses several risks associated with moisture accumulation in walls, mould growth, wood rot, frost damage and condensation risks. Engineers, architects, building owners and policy makers do not have clear guidelines on implementing energy efficiency measures and ensuring that energy savings will be reached and buildings preserved. Therefore, this research demonstrates how to plan the moisture safe and sustainable renovation of historic buildings. During this study, several technical solutions and dynamic modelling possibilities have been tested, allowing the renovation of historic buildings by insulating the walls from the inside. Long-term in-suit measurements in actual buildings and laboratory allow assessing long-term effects of internal insulation.

The first available data on masonry buildings in Latvia are from the12th century. Based on the literature review and surveys of existing historic buildings, the analysis of the most common historic building envelope deteriorations related to moisture accumulation in structures, mould formation, salt release and wall damages was performed. The research shows that building's technical condition must be considered when evaluating building potential for retrofit, as energy consumption and technical condition are linked. Therefore, the pre-assessment method has been developed and reviewed. Using this method, it is possible to evaluate the performance of each building against listed modes of failure, thereby also to spot the main problems which require immediate action. Also, the research demonstrates the possibilities and limitations of non-destructive measurements in the project pre-assessment stage. It is proven that moisture movement in external walls influences energy consumption and building's durability, mechanical stability, lifetime, and the health and safety of its residents.

To expand the possibilities of hygrothermal model processes in historic masonry walls, testing of samples of brick and natural stone used in Latvia was performed, determining material density, open porosity, water vapour permeability, water absorption, thermal conductivity, specific heat capacity and salt composition in masonry materials, frost resistance and pressure. In total, testing of hygrothermal characteristics of more than 60 Latvian historical bricks was performed. Samples were taken from 24 buildings in Latvia. The research carried out on the historical brick masonry allowed collecting data to represent a start-up for further investigations. Laboratory tests reveal that historical clay bricks are highly inhomogeneous and anisotropic, as the results show substantially large dispersion. Based on the obtained results, additions to the construction material database of modelling program DELPHIN 6 have been prepared. The research proved how crucial is correct and reliable input data regarding material parameters when modelling hygrothermal processes in historic masonry walls.

By creating and testing the internally insulated wall made of historic bricks in laboratory conditions, the currently most frequently used insulation materials – mineral wool and polystyrene – were tested, as well as more innovative but less popular insulation materials such as aerogel and wood fibre. Besides, in actual buildings, the most used mineral wool, vacuum insulation panel and aerogel were evaluated. The findings of the laboratory experiment demonstrated that when internal insulation is applied to historic masonry in a cold climate, careful assessment of hygrothermal behaviour of combined historic masonry and insulation material wall construction has to be carried out, after a thorough determination of the properties of the materials used. It is possible that simulation results will not conform precisely to actual measured data due to the influence of values of initial moisture content of the wall and material parameter values, both playing an essential role in the simulation.

Throughout the year, long-term measurements have been performed in the internally insulated historic buildings of various size, intended use and age, measuring heat transfer and temperature distribution within the external walls. The measurements are supplemented with dynamic modelling of the hygrothermal processes in program DELPHIN.

During the research, an approach to the dynamic modelling of the hygrothermal processes in internally insulated structures is proposed, allowing the planning of sustainable renovation of historic buildings. The proposed approach makes it possible to explain why and how insulation of walls from the inside can cause or exacerbate moisture problems in structures that have not previously had such problems. With the help of construction materials testing, simulation programs TRNSYS and DELPHIN, dynamic simulation models for modelling the hygrothermal processes in building external structures have been developed. The developed simulation models were validated by comparing the obtained calculation data with long-term measurements in buildings and the laboratory. A total of 8 in-depth analyses of thermal insulation systems under laboratory conditions and 5 studies of thermal insulation systems in actual buildings used for wall insulation from the inside were performed. The results of hygrothermal modelling validate the reliability of prediction of hygrothermal conditions and risk of mould growth and frost damage in internally insulated historic buildings. Thus, the first hypothesis was approved – it is possible to predict the hygrothermal performance of internally insulated structures through dynamic simulation, therefore assessing and preventing risks associated with the restoration of historic buildings. Material parameters and initial conditions are vital for the results and reliability of the modelling. Nevertheless, reliable hygrothermal conditions can be predicted with hygrothermal simulations concerning the given modelling input.

In the case study buildings, the reduction of heat energy consumption was determined. The inside microclimate was evaluated by performing temperature and relative humidity measurements in the premises and humidity, heat transfer and temperature measurements in the walls. The research demonstrated that internal insulation makes it possible to reach heat transfer coefficient reduction to 0.273 W/(m^2K) or even to 0.060 W/(m^2K) depending on the used insulation material and its thickness. The achieved results show that by insulating the walls of a historic building from the inside, it is possible to provide 30 % to 75% reduction, providing good indoor comfort (average temperature during the heating season around

+21 °C, relative humidity from 30 % to 50 %). Furthermore, the modelling results prove that they can well characterize and describe the hygrothermal processes in structures. So, the second hypothesis also is true – it is possible to reduce energy consumption in historic buildings by applying internal insulation, preserving their cultural and historical value and not creating additional risks of structural damage.

Energy efficiency renovation of historic buildings in a cold climate is a very complex problem due to the hygrothermal behaviour of the building envelope. Many factors, such as construction material physical and chemical properties, indoor and outdoor climate, installation quality, the initial condition of original wall, and other factors influence the outcome of the energy efficiency project. Nevertheless, these projects can be implemented with a prior assessment and modelling of hygrothermal behaviour.