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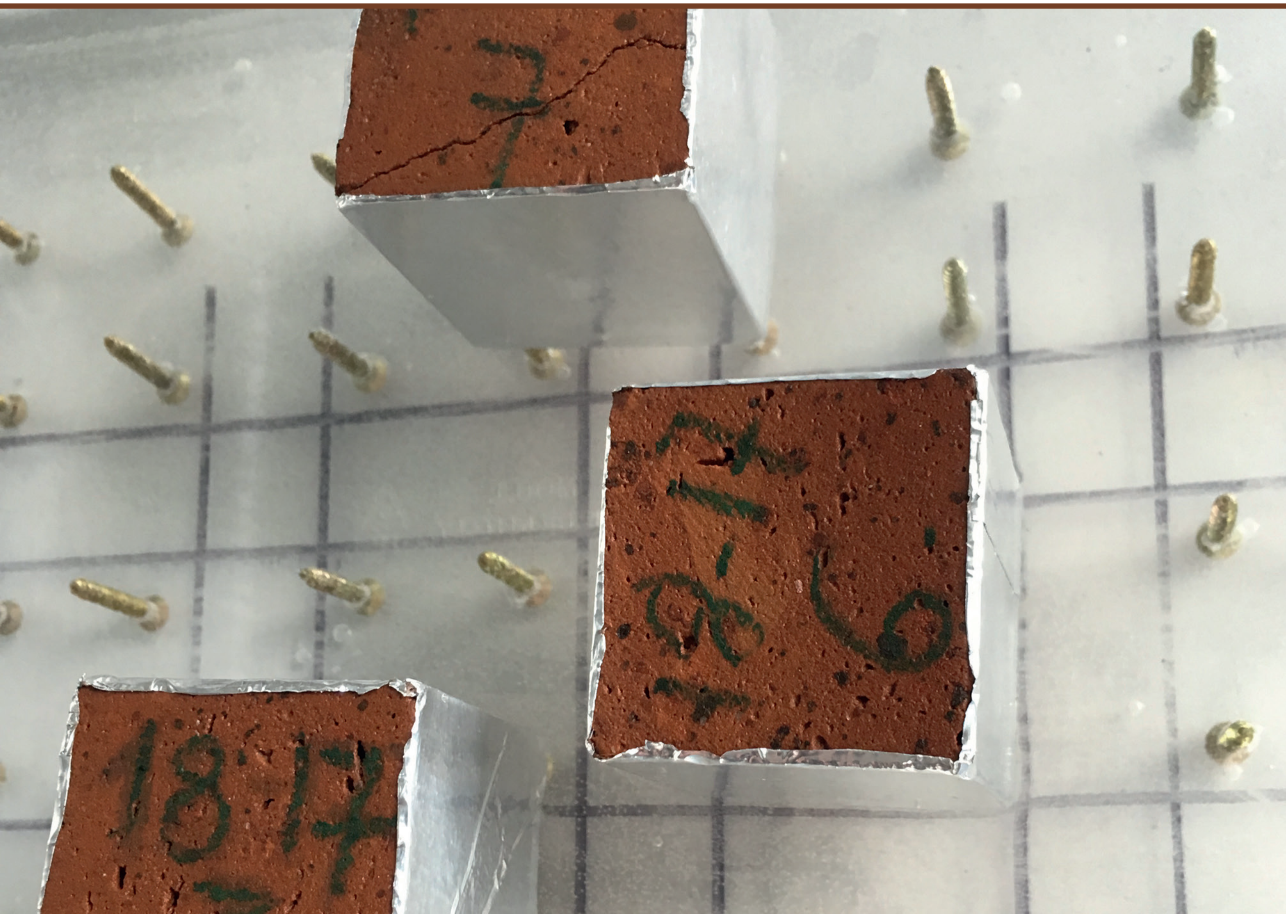
Ritvars Freimanis

HYGROTHERMAL PROCESSES IN POROUS MATERIALS

Summary of the Doctoral Thesis



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

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"Environmental Engineering"

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Summary of the Doctoral Thesis

Scientific supervisor
Professor Dr. sc. ing.
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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 defense at the open meeting of the RTU Promotion Council on 21. December, 2023 at 14:00 at the Faculty of Electrical and Environmental Engineering of Riga Technical University, 12/1 Azenes Street, Room 212.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for review to Riga Technical University for promotion to the scientific degree of Doctor of Engineering Sciences is my own. I confirm that this Doctoral Thesis has not been submitted to any other university for promotion to a scientific degree

Ritvars Freimanis ……………………………. (signature)

Date: ……………………

The Doctoral Thesis has been written in Latvian and contains an introduction, 3 chapters, conclusions, a list of references, 36 pictures, 4 tables, and 10 appendices; the total number of pages is 213. The bibliography contains 59 titles.

CONTENTS

INTRODUCTION

Actuality

In Europe, one of the largest energy consumers is the building sector, which accounts for approximately 40 % of total energy consumption and about 36 % of total CO_2 emissions in the European Union. Furthermore, only 25 % of the EU's building stock is classified as energy efficient, and forecasts show that in 2050, 85–95 % of existing buildings will still be in operation [1]. The population's demand for increased comfort and the growing trend of using electrical equipment, as well as other factors, contribute to the increase in energy consumption, which is one of the causes of climate change. There are several areas where it would be possible to use energy more efficiently, reducing consumption and thus greenhouse gas emissions. Therefore, to achieve carbon neutrality by 2050, the European Union has set ambitious goals that include increasing the energy efficiency of buildings, using renewable energy resources, and reducing greenhouse gas emissions [2].

Building insulation is an effective measure for improving the energy efficiency of buildings, but in order to achieve these goals, a solution to the dilemma between cultural and historical heritage and energy efficiency has been found because the built environment is an essential cultural asset that creates the necessary living environment and affects the quality of life [3]. One solution to this dilemma could be to insulate historic buildings from the inside, preserving the appearance of the facade and increasing energy efficiency at the same time. However, such a solution can cause unwanted, unexpected changes in the building's hygrothermal processes, potentially causing problems such as mould, crumbling bricks, salt stains, etc.

A hygrothermal assessment is essential when considering the use of internal insulation. Detailed planning reduces the risk associated with changes in hygrothermal behaviour. When planning, various factors must be taken into consideration, such as the characteristics of the bricks in the original masonry, thermal insulation materials, and outdoor and indoor boundary conditions. The quantitative relationship between different factors and their overall impact on moisture risk is still unclear, and due to the complex interaction of factors, the evaluation of moisture risk is difficult. As a result, the planning and selection of measures for the energy efficiency of historic buildings and city blocks of historic buildings is a complex process, which includes the need for building owners and managers to assess the risks and benefits of warming buildings from the inside.

Research questions

1. Can a positive energy balance block be achieved in a historical urban structure?
2. What are the moisture-proof internal thermal insulation systems that can be incorporated into energy efficiency renovation projects to help achieve a positive energy balance for a historic-built city block?

Research purpose and tasks

The research aims to evaluate the possibilities of creating a positive energy balance quarter in a cultural and historical urban environment using moisture-proof insulation of buildings from the inside.

To achieve the goal, the following tasks were defined:

1. To evaluate the hygrothermal parameters of the historical masonry and stone exterior wall materials.
2. To evaluate the effect of hygrothermal parameters of historical exterior wall materials on hygrothermal processes in a wall insulated from the inside.
3. To assess the use of thermal insulation materials and systems for warming from the inside.
4. To evaluate the effect of internal insulation on hygrothermal processes and potential energy savings in a natural stone masonry wall and a brick wall insulated with vapour-tight thermal insulation.
5. To evaluate creating of a positive energy balance block in a historical urban environment.
6. Assess the potential of energy efficiency solutions in a historic city block.

Proposed hypotheses

Hypothesis 1. Historic bricks have different hygrothermal properties and affect the hygrothermal processes in internally insulated solid masonry walls.

Hypothesis 2. Climatic outdoor conditions affect hygrothermal processes from the inside in solid masonry walls insulated from the inside.

Hypothesis 3. Historical insulating masonry and stone walls from the inside with vapour-impermeable thermal insulation in cold climates is a safe measure to increase energy efficiency.

Hypothesis 4. Preservation of historical buildings does not allow achieving a positive energy balance in the historical city blocks.

The hypotheses mentioned above were studied with various scientific research methods, which are reflected in more detail in scientific publications.

Hypothesis 1. Historic bricks have different hygrothermal properties, and they affect hygrothermal processes in solid masonry walls insulated from the inside.

1. Analysis of scientific literature.
2. Collection of forty historical brick samples and testing of hygrothermal properties.
3. Creating *Delphin* files for the computer simulation tool.
4. Formation of clusters of tested bricks.
5. Computer simulation with external masonry walls made of tested bricks and insulation from the inside with capillary active thermal insulation material.

The research methods used and the results obtained are described in the following publications:

- **Publication A**. Freimains, R., Zundans, Z., Balins, R., Blumberga, A., Vanaga, R. (2021). Hydrothermal Properties of Historic Bricks from Various Sites of Latvia [Data set]. *Zenodo* . *https://doi.org/10.5281/zenodo.5575101*) The publication is a data set, which includes the results of hygrothermal parameter testing of 40 different Latvian historical brick samples (from the 17th to the 20th century). Standard measurement methods with some adjustments were used to determine the hygrothermal parameters of the brick samples. The obtained parameters were used to create material files in the simulation tool *Delphin*.
- **Publication B**. Freimanis, E., Blumberga, A., Vanaga, E., Zundāns, Z. Evaluation of the Impact of Bricks of Various Characteristics on Internally Insulated Masonry Walls in Cold Climate*, Buildings 2023, 13, x*. *https://doi.org/10.3390/xxxxx* (accepted for publication). The main goal of this study was to cluster the 40 historical bricks found in Latvia, which were tested in Publication A. This was done using the hygrothermal properties of the bricks and the *Delphin* simulation results – the hygrothermal properties clustering results were cross-checked with the *Delphin* simulation data clustering results. Two of the nine clusters contained 67.5 % of all samples, four clusters contained only one sample, and other clusters contained two, three, and four samples.
- **Publication C**. Freimanis, R., Zundans, Z., Balins, R., Vanaga, R., Blumberga, A. Finding the Generic Hygrothermal Properties of Historical Bricks by Supervised Agglomerative Clustering*, Environmental and Climate Technologies, 2022, 26(1), pp. 1234–1243. https://doi.org/10.2478/rtuect-2022-0093* . The aim of this study was to evaluate the effect of a vapour- permeable capillary-active calcium silicate thermal insulation system on the hygrothermal behaviour of different historical brick masonry in cold climates with and without adhesive, when the insulation is done from the room side. The results of the tests described in Publications A and B on the hygrothermal properties of 40 historical bricks were used in the numerical experiments. The study evaluated the effect of brick type, the quality of calcium silicate used, and cold climate on hygrothermal behaviour. The results showed that the temperature behaviour is similar for all wall types, whereas there is a large difference in the humidity behaviour.

Hypothesis 2. Climatic outdoor conditions affect hygrothermal processes from the inside in massive masonry walls.

1. Analysis of scientific literature.
2. Laboratory tests and computer simulations of heating systems under constant conditions.
3. Laboratory tests and computer simulations of heating systems under dynamic conditions.
4. Testing of a new thermal insulation material for use in internal insulation.

The research methods used and the results obtained have been published in the following publications:

- **Publication D.** Biseniece, E., Freimanis, R., Purvins, R., Pumpurs, A., Blumberga, A. Study of Hygrothermal Processes in External Walls with Internal Insulation*, Environmental and Climate Technologies, 2018, 22(1), pp. 22–41*. *https://*

doi.org/10.1515/rtuect-2018-0002. As part of this study, a comparison of the hygrothermal simulation results with the experimental results obtained from the testing of internally insulated historic brickwork was carried out. The study was conducted with four thermal insulation materials (mineral wool, EPS, wood fibre and granular aerogel) in a cold climate (on average 4000 heating degree days). The results showed that there are differences between the measured and simulated hygrothermal indicators of the studied structures, and they are caused by the differences between the parameters of the materials used and the initial conditions.

- **Publication E.** Freimanis, R., Vanaga, R., Balodis, V., Zundans, Z., Blumberga, A. Hygrothermal assessment of insulation systems for internal insulation of solid masonry walls under various conditions, *Buildings 2023, 13(10), 2511; https://doi.org/10.3390/buildings13102511*. This study evaluates the hygrothermal performance of solid masonry walls with seventeen thermal insulation systems subjected to various external boundary conditions, including a steady-state cycle, a dynamic dry cycle, a wind-driven cycle, and a drying cycle. During the experiments, the relative humidity and temperature under the insulation were measured. In addition, relative humidity changes in the masonry were measured. The results showed that the tested thermal insulation systems have similar thermal performance, while different moisture performance. Vapour-tight and vapour-tight insulation systems have different hygrothermal behaviour in different test cycles depending on the vapour diffusion resistance of the material. Numerical simulations are sensitive to the hygrothermal properties of materials.
- **Publication F.** Blumberga, A., Freimanis, R., Muizniece, I., Spalvins, K., Blumberga, D. Trilemma of historic buildings: Smart district heating systems, bioeconomy, and energy efficiency, *Energy 2019, 186, art. from 115741. https://doi.org/10.1016/j.energy.2019.07.071*. This study evaluates the applicability of an innovative thermal insulation material of pine needles as an internal thermal insulation material for historic massive walls. The results show that the studied material is very porous and has high moisture transfer and moisture accumulation capacity.

Hypothesis 3. Historical insulating masonry and stone walls from the inside with vapor-impermeable thermal insulation in a cold climate is a safe measure to increase energy efficiency.

1. Analysis of scientific literature.
2. Taking measurements in two buildings insulated from the inside with a vapour barrier.
3. Computer simulation of hygrothermal processes in the exterior walls of two buildings insulated from the inside with a vapour-impermeable barrier.
4. Analysis of energy consumption in two buildings insulated from the inside with a vapour barrier.

The research methods used and the results obtained are described in the following publications:

- **Publication G.** Blumberga, A., Freimanis, R., Biseniece, E., Kamenders, A. Hygrothermal Performance Evaluation of Internally Insulated Historic Stone Building in a Cold Climate*, Energies, 2023, 16(2), 866. https://doi.org/10.3390/en16020866*. The aim of this study was to perform long-term monitoring of the hygrothermal behaviour of an internally warmed historic dolomite stone wall. The monitoring results are compared with 1D hygrothermal simulations and building energy consumption simulation. The measurement results and hygrothermal evaluation showed that energy consumption had decreased by 55 %, with the relative humidity under the insulation remaining at 60 % most of the time, but temporarily increasing by 80 %. Energy consumption simulation showed energy savings potential of up to 72 %, with proper energy management.
- **Publication H.** Freimanis, R., Vaiskunaite, R., Bezrucko, T., Blumberga, A. In-situ Moisture Assessment in External Walls of Historic Building Using Non-destructive Methods, *Environmental and Climate Technologies, 2019, 23(1), pp. 122–134. https://doi.org/10.2478/rtuect-2019-0009*. In this study, in situ measurements of humidity and temperature were made from the inside of insulated brickwork in a historical building in Old Riga. The results showed that moisture problems do not increase in the cold months of the year: condensation does not form under the internal thermal insulation, and there is no risk of mould formation. However, the facade of the building was significantly affected by climatic conditions, and the humidity of the masonry increased during rain.

Hypothesis 4. Preservation of historical buildings does not allow achieving a positive energy balance in the historical city quarters.

1. Analysis of scientific literature.
2. Multi-criteria analysis of the transition of the historical quarter to a positive energy quarter from the aspects of architecture and building energy efficiency.
3. Energy balance evaluation for the transition of the historical quarter to a positive energy quarter.

The methods used and the results are reflected in the following publications:

- **Publication I.** Blumberga, A., Vanaga, R., Antuzs, J., Bondars, E., Treija, S. Is the High Quality Baukultur a Monkey Wrench in the Global Climate Challenges? *Environmental and Climate Technologies, 2019, 23(3), pp. 230–244. https://doi.org/10.2478/rtuect-2019-0092*. This paper describes a dual multi-criteria analysis evaluating city blocks from both energy efficiency and cultural heritage perspectives. The proposed multi-criteria analysis criteria to assess cultural heritage, liveability and energy efficiency potential characterize the specific characteristics of a city block. The obtained results show that the blocks with higher cultural value have + lower energy efficiency potential and vice versa.
- **Publication J.** Blumberga, A. , Vanaga, R., Freimanis,R., Bondars, E., Treija, S. Transition from Traditional Historic Urban Block to Positive Energy Block*, Energy, 2020, 202, 117485. https://doi.org/10.1016/j.energy.2020.117485.* The study focuses on the transition from a traditional city block to a positive energy

block in the environment of the historic city centre. It analyses energy consumption data and develops a concept for opportunities to reduce energy consumption, as well as produce renewable energy in the block and recover thermal energy from data centres and cooling units. The results show that very ambitious energy efficiency improvement targets are needed to achieve a positive energy quarter.

The scientific novelty of the research

- Testing of hygrothermal parameters of bricks of historical buildings in Latvia and formation of clusters was carried out.
- Testing was done of various thermal insulation materials and systems in laboratory conditions for use for internal insulation in historic masonry buildings in a cold climate.
- Long-term in-situ measurements on the insulation of historic stone exterior walls in a real building in a cold climate were carried out.
- A double multi-criteria analysis was developed, which was used to select a historical city block according to cultural-historical and energy efficiency criteria.
- An assessment of the creation of a positive energy balance quarter in a cultural and historical urban environment was carried out.

Practical application of the research results

The results obtained in the research are essential for civil engineers, architects and other specialists related to building renovation and insulation. The measurements and data obtained in the research facilitate the planning and selection of measures for the energy efficiency of historical buildings and city blocks of historical buildings. The files of hygrothermal parameters of historical bricks obtained in Latvia created in the research are available to every specialist who plans to perform mathematical modelling of the insulated structure. The conclusions and insights obtained in the study can help building owners and managers assess the risks and benefits of warming buildings from the inside. The results obtained in the research are important for policy makers not only at the national level, but also at the local government level, as they will allow the creation of normative documents related to the renovation of buildings, which are based on science. They can be related to various constructive building insulation solutions as well as to the transformation of city blocks into positive energy balance blocks.

Approbation of research results

Scientific publications on the topic

1. Freimains, R., Zundans, Z., Balins, R., Blumberga, A., Vanaga, R. (2021). HYGROTHERMAL PROPERTIES OF HISTORIC BRICKS FROM VARIOUS SITES OF LATVIA [Data set]. *Zenodo* . *https://doi.org/10.5281/zenodo.5575101.*
2. Freimanis, R., Blumberga, A., Vanaga, R., Zundans, Z. Evaluation of the Impact of Bricks of Various Characteristics on Internally Insulated Masonry Walls in Cold Climate*, Buildings 2023, 13, x*. *https://doi.org/10.3390/xxxxx* (accepted for publishing).
3. Freimanis, R., Zundans, Z., Balins, R., Vanaga, R., Blumberga, A. Finding the Generic Hygrothermal Properties of Historical Bricks by Supervised Agglomerative Clustering*, Environmental and Climate Technologies, 2022, 26(1), pp. 1234–1243. https://doi.org/10.2478/rtuect-2022-0093*
4. Biseniece, E., Freimanis, R., Purvins, R., Pumpurs, A., Blumberga, A., Study of Hygrothermal Processes in External Walls with Internal Insulation*, Environmental and Climate Technologies, 2018, 22(1), pp . 22–41* . *https://doi.org/10.1515/rtuect-2018-0002*
5. Freimanis, R., Vanaga, R., Balodis, V., Zundans, Z., Blumberga, A., Hygrothermal assessment of insulation systems for internal insulation of solid masonry walls under various conditions, *Buildings 2023, 13(10), 2511; https://doi.org/10.3390/buildings13102511*
6. Blumberga, A., Freimanis, R., Muizniece, I., Spalvins, K., Blumberga, D., Trilemma of historic buildings: Smart district heating systems, bioeconomy and energy efficiency, *Energy 2019, 186, art. from 115741. https://doi.org/10.1016/j.energy.2019.07.071*
7. Blumberga, A., Freimanis, R., Biseniece, E., Kamenders, A. Hygrothermal Performance Evaluation of Internally Insulated Historic Stone Building in a Cold Climate*, Energies, 2023, 16(2), 866. https://doi.org/10.3390/en16020866*
8. Freimanis, R., Vaiskunaite, R., Bezrucko, T., Blumberga, A. In-situ moisture assessment in external walls of historic building using non-destructive methods, *Environmental and Climate Technologies, 2019, 23(1), pp. 122–134. https://doi.org/10.2478/rtuect-2019-0009*
9. Blumberga, A., Vanaga, R., Antuzs, J., Bondars, E., Treija, S., Is the High Quality Baukultur a Monkey Wrench in the Global Climate Challenges? *Environmental and Climate Technologies, 2019, 23(3), pp. 230–244. https://doi.org/10.2478/rtuect-2019-0092*
10. Blumberga, A., Vanaga, R., Freimanis, R., Bondars, E., Treija, S. Transition from traditional historic urban block to positive energy block*, Energy, 2020, 202, 117485. https://doi.org/10.1016/j.energy.2020.117485*

The results of the Doctoral Thesis were presented at 3 international scientific conferences:

1. International scientific conference “Environmental and climate technologies”, CONECT, 2022, Riga, Latvia.
2. International scientific conference “Environmental and climate technologies”, CONECT, 2020, Riga, Latvia.
3. International scientific conference “Environmental and climate technologies”, CONECT, 2019, Riga, Latvia.

Structure and scope of the Thesis

The Thesis is based on ten thematically unified scientific publications. These publications and research results have been presented and approved at several international conferences and are available in scientific information repositories and included in international databases. The Doctoral Thesis was written in Latvian. Its structure is based on the research on the energy efficiency of historical buildings, which consists of four main topics (see Fig. 1):

1. Building materials and constructions of historical buildings.
2. Thermal insulation materials and systems.
3. The use of internal insulation in historic buildings.
4. A block of positive energy balance in a historic urban environment.

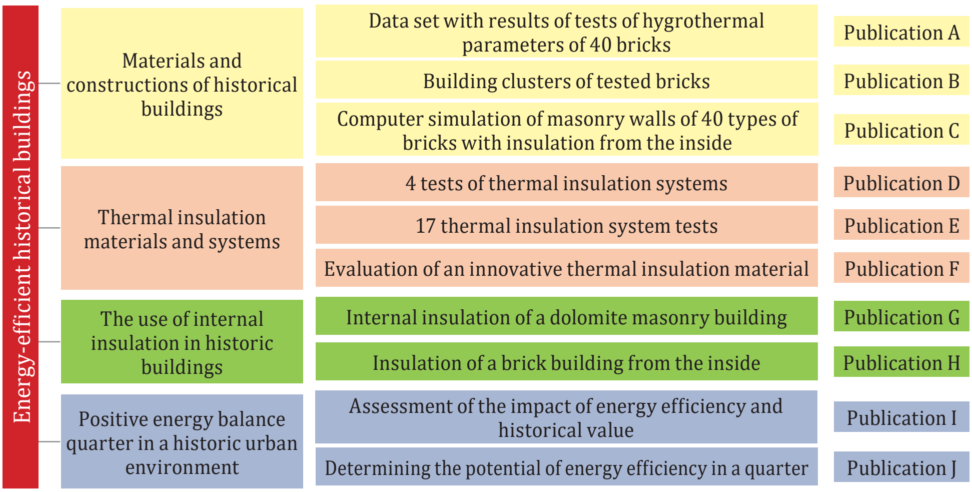

Fig. 1. Thematic structure of the Thesis.

The thesis consists of an introduction, three chapters, conclusions, and a list of literature. In the introduction, the purpose of the work and the tasks to be performed for its implementation are set, and the scientific and practical significance of the research is described. Chapter 1 provides a review of the literature on the researched topics. Chapter 2 presents research methods related to the energy efficiency of historical buildings and four research subtopics (see Fig. 1). Chapter 3 discusses the research results. At the end of the Thesis, the conclusions are summarized in accordance with the proposed hypotheses. There are 59 titles in the reference list of the Doctoral Thesis.

1. RESEARCH METHODOLOGY

This chapter describes the scientific research methods used in the work. They have been detailed in scientific journal publications and presented at international conferences, and references to these publications (see the list of publications in the introductory chapter) are used throughout the chapter. Within the framework of the Thesis, various scientific research methods were used, including mathematical modelling, testing materials and structures in the laboratory, taking measurements in real buildings, and using a multi-criteria analysis.

1.1. Materials and constructions of historical buildings

In order to be able to perform computer simulations for warming external walls from the inside, output parameters for the hygrothermal properties of each material used in the simulation are required. The accuracy of the simulation results depends on the suitability of the input data for the particular wall, so the values of the material parameters should be as close as possible to the parameter values of the investigated wall. The computer program *Delphin* developed at the Technical University of Dresden was used in this study.

As part of the research, 40 historical brick samples were collected from different regions of Latvia. The samples were collected by looking for the buildings that were being renovated or demolished, or that had fallen into disrepair. The maximum number of samples was determined by the testing capacity of the laboratory.

The hygrothermal properties of the collected samples were tested. Table 1.1 shows the standardized testing methods of the collected brick samples used in the study [4].

Table 1.1

Methods of Testing the Brick Samples Used in the Study

Density	EN 772-13:2000. Test methods for masonry units. Determination of net and gross dry density of masonry units (except for natural stone).
Porosity	EN 772-3:1998. Test methods for masonry units. Determination of net volume and percentage of void of clay masonry units by hygrostatic weighing.
Vapour permeability	CUP-Test (μ values). EN ISO 12572:2001 – Hygrothermal performance of building material and products. Determination of water vapour transmission properties.
Water absorption	ISO 15148:2002, 2002. Hygrothermal performance of building material and products. Determination of water absorption coefficient by partial immersion.

In order to be able to create the necessary files for the *Delphin* computer program, some deviations from the testing standards were made according to the test descriptions developed by the Dresden University of Technology. The methods used are described in Table 1.2.

Table 1.2

Testing Methods According to the Descriptions of the Technical University of Dresden

Moisture accumulation	Hygroscopic sorption and water accumulation properties are tested according to the method developed at the Dresden University of Technology based on DS/EN ISO 12571:2013 Hygrothermal performance of building material and products. Determination of hygroscopic sorption properties and (DS/EN ISO 11274). Soil quality. Determination of the water-retention characteristics. Laboratory methods.
Drying curve	A non-isothermal combined vapour and liquid transfer testing method has been developed at the Dresden University of Technology.
Heat capacity and thermal conductivity	Heat pulse technology with ISOMET equipmen.t

In the next step, the obtained testing results were used for clustering by creating hierarchical clustering dendrogram, which was made with agglomerative clustering method. Machine learning (ML) clustering analysis with *Jupyter* was used to cluster the samples [5]. *Python* libraries from *SciKit Learn* were used for clustering [6]. The *Python libraries* used were *Sklearn* and *Matplotlib*. *Sklearn* is based on *NumPy* and *Scipy*, and it is used for the computation of the clustering process. *Matplotlib* is used to visualize the results, including a dendrogram. Before clustering, all data records were normalized with the *StandardScaler* function built into the *Sklearn* library. Data normalization is necessary so that some data do not have more weight than other results. Clustering analysis generates all possible cluster count solutions, meaning that at one end of the spectrum, all samples are in one large cluster, while at the other end of the spectrum, each sample forms a separate cluster [7].

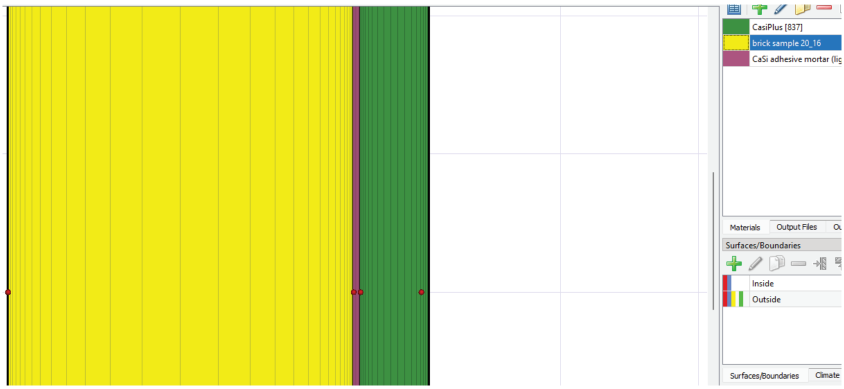

Fig. 1.1. Simulation model used to compare 40 wall types.

The created *Delphin* files were used in the next step of the research to perform a computer simulation in the *Delphin* software with the 40 tested bricks from which a wall, insulated from the inside with calcium silicate, was created. Figure 1.1 shows the modelled external wall structure with brickwork (0.25 m) and calcium silicate thermal insulation (0.05 m). Two simulations were performed for each of the 40 types of masonry: with and without glue under the insulation material [8].

For the outdoor climate, the data collected by the Latvian Centre for Environment, Geology and Meteorology for the year 2022 from the meteorological station of the University of Latvia were used [9]. Indoor climate conditions were set as a function of the outdoor temperature. The simulation period was 3 years.

1.2. Thermal insulation materials and systems

The laboratory tests carried out in this section of the study were carried out in the climate chambers (outdoor climate chamber and room climate chamber) located in the laboratory [10], [11]. The test specimens were built into a test wall, which was placed between the two chambers during the testing to allow the tests to be performed under controlled conditions (see Fig. 1.2). An outdoor climate chamber simulates outdoor conditions by dynamically controlling the chamber temperature, relative humidity, wind-driven rain, and solar radiation. The room climate chamber simulates indoor conditions; in this chamber, the necessary microclimate is provided by changing the relative humidity and temperature. The outdoor climate chamber is equipped with a water spray and collection system on the outer side of the structure to simulate the effect of wind-driven rain (when rain is driven by wind, a large amount of water acts on vertical surfaces). The system consists of 9 nozzles, one for each wall sample, a pump, plastic pipes for the water distribution system, and the water collection system. Solar radiation simulation lamps simulate the effects of the sun.

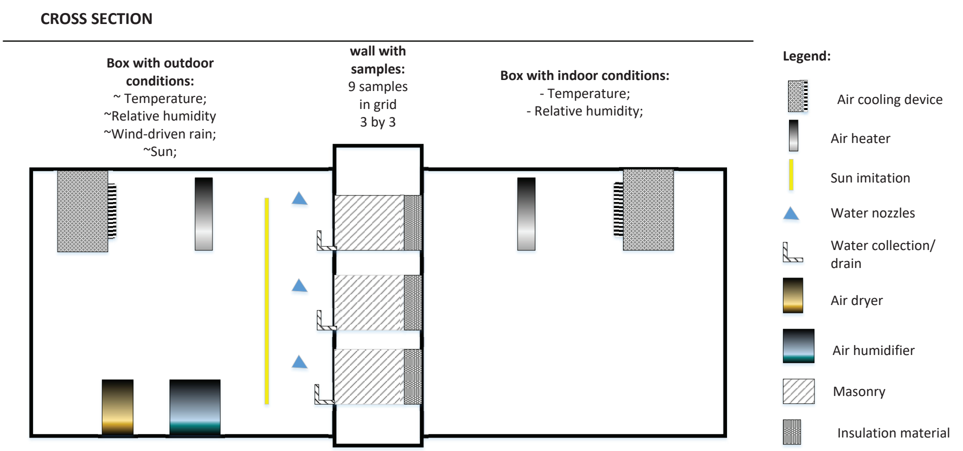

Fig. 1.2. Climate chamber's schematic representation.

The relative humidity between the insulation layer and the masonry was measured using the *Honeywell HIH 4000* series humidity sensors. Moisture sensors were installed under the insulation layer along with K-type thermocouples. The sensors of each sample measured the conditions between the insulation layer and the masonry wall, where there was a significant risk of condensation. The *Campbell Scientific CR1000* data logger recorded the data to the computer. The measurement time interval was 1 minute.

Eighteen thermal insulation systems were tested in one of the stages of the study. Each system consisted of thermal insulation material with or without a vapour barrier, adhesive and external finish (some systems do not). Some systems were built according to the manufacturer's instructions (mineral wool with vapour barrier, EPS (2 types), XPS, PIR with Sika cement layer and fiberglass mesh, cork, expanded cork, aerogel blanket). Other systems were intentionally designed differently from the instructions in order to test the hygrothermal behaviour of the materials, for example, vapour permeable materials were installed without a vapor barrier: stone wool, expanded clay, cellulose, three types of fibreboard with different densities, and a particle board without exterior finish. Thermal insulation materials have various origins and include both vapour-tight and vapour-impermeable materials. Gypsum plaster was excluded from the results because the relative humidity sensor did not work during the tests. The thermal insulation systems used in the tests are materials obtained from inorganic minerals: mineral wool with vapour barrier, stone wool, expanded clay, gypsum plaster and aerogel blanket. Materials derived from organic fossil fuels are EPS (2 types), XPS, PIR with Sika cement layer and fibreglass mesh (on the outside), PIR with aluminium coating and VIP. Biological materials of plant/animal origin are cellulose, three types of wood fibre boards with different densities: cork, expanded clay and planing chipboard. The material properties were obtained from the manufacturer's technical data sheets or by contacting the manufacturers directly. Information was available on the thermal properties of the material, such as thermal conductivity λ, but other parameters, such as specific heat or vapour resistance, were missing in the technical data sheets of some products.

Each insulation system was attached to a masonry sample constructed from industrially produced new bricks (see Fig. 1.3). The new bricks were used to reduce the impact of material property uncertainty. Before starting the measurements, the bricks were kept in room conditions so that the wall samples could dry.

Outdoor climate chamber parameter values for all cycles were based on weather data from 2014 to 2018 to simulate outdoor environmental conditions. They were obtained from a database of public observations. The criterion for choosing a month for modelling the cycle of temperature fluctuations was the largest amplitude of daily temperature fluctuations, so the outdoor air parameters corresponded to May. The experimental design was based on the following conditions in the chambers:

- Room climate chamber temperature +20 °C, relative humidity 50 %.
- The temperature of the outdoor climate chamber under equilibrium conditions is +10 °C, and the relative humidity is 50 %. For dynamic cycles,

temperature and relative humidity correspond to outdoor daily fluctuations in May (see Fig. 1.4). Wind-driven rain 0.278 $l/m^2 \cdot s$ (5 minutes daily) and solar radiation 300 W/m^2 (8 hours daily).

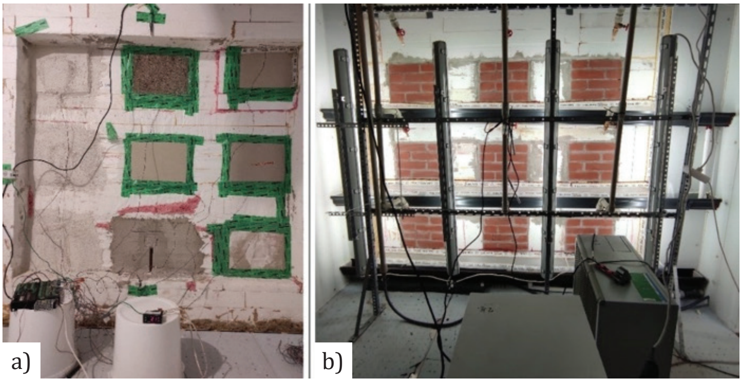

Fig. 1.3. Test wall With nine masonry wallsamples a) from warm side b) from the cold side.

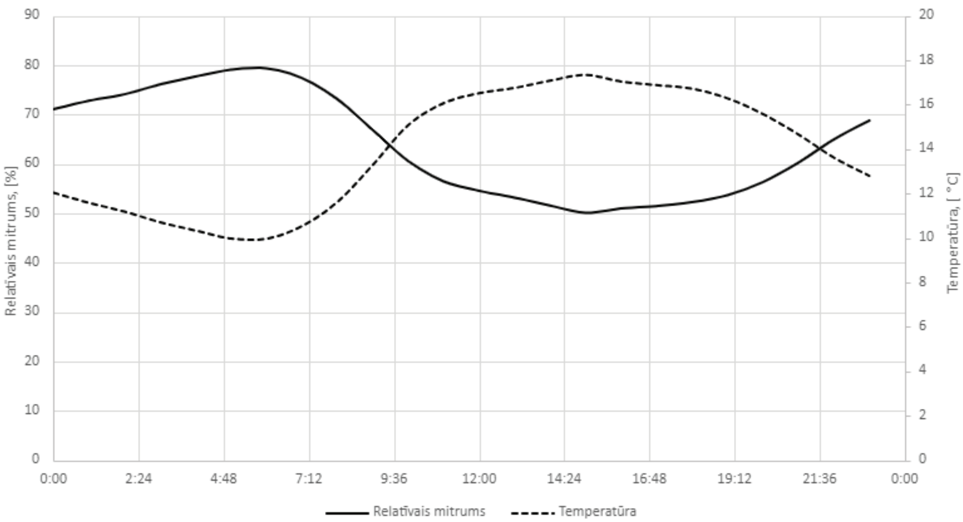

Fig. 1.4. Diurnal climate fluctuations in May selected as the basis for the dynamic test cycle.

In this phase of the study, in addition to relative humidity and temperature measurements, masonry moisture measurements were performed under the insulation with non-invasive measurement methods (dielectric and microwave probes). Non-invasive humidity measurements were taken before and after each test cycle five times during the test. *Trotec T3000* was used for the measurements. A microwave probe was used to measure humidity at a depth of 20 cm, and a dielectric probe at a depth of 2 cm.

The first nine systems tested in the laboratory were simulated in *Delphin* under steady-state conditions using similar materials from an existing material database. The materials were selected based on the specifications provided by the manufacturers for the original materials used in the laboratory experiment. These simulations were performed under both changing outdoor climate conditions and constant conditions to obtain data and compare them with the measurement data obtained in the laboratory experiment. The initial temperature and relative humidity conditions of the simulations were set to match those measured at the beginning of the experiment, and the outdoor relative humidity was increased to 93 % to match the conditions maintained in the climate chamber. The time frame of the simulations was set to 1 hour. Each isolation system was also modelled in the *Delphin* software (see Fig. 1.5). The *Delphin* file was created for the hygrothermal properties of the bricks used in the test walls.

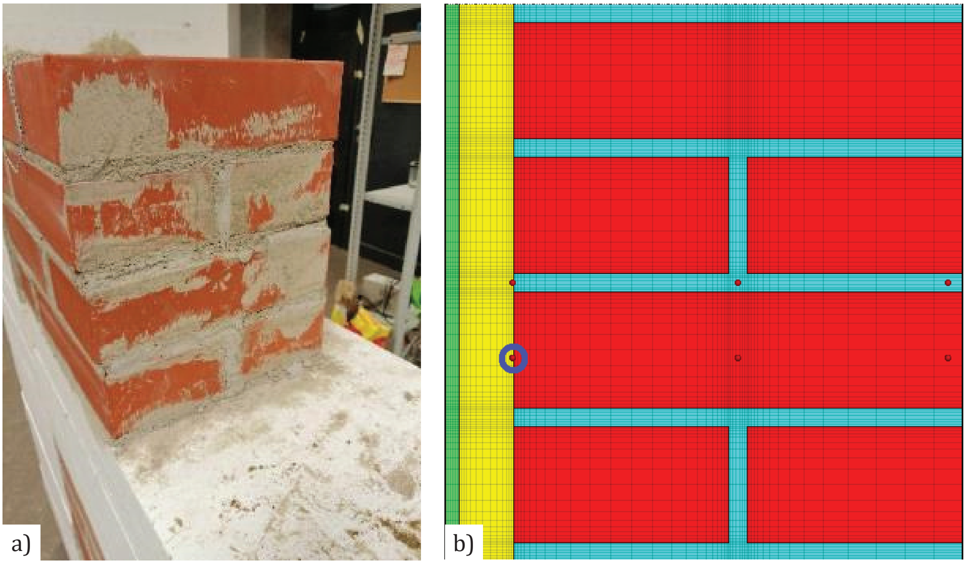

Fig. 1.5. Test wall sample a) in the laboratory and b) in the Delphin model.

1.3. The use of internal insulation in historic buildings

The first study was conducted in a single-family building in *Seces* parish, *Aizkraukle* district, Latvia [12]. It was built in 1893 as a country house. In the period after the Second World War until the 21st century, the building was poorly maintained; the basement was used as cattle shed, resulting in serious damage to the wooden beams and the covering of the first floor. In 1992, the building was denationalized and the family of the original owner of the building regained the ownership.

The building has two floors with a total heated area of 339 m^2 and a volume of 870 m^3. The basement (floor area 68 m^2 and volume 130 m^3) occupies half of the building's area of the southeast facade and is not heated. The total area of the facade is 274 m^2, including windows and doors, but excluding the basement.

The exterior walls are built of locally sourced dolomite stone embedded in mortar. Granite stones are also used for the basement walls. Granite chips cover mortar joints between the dolomite stones (see Fig. 1.6).

The dolomite samples from the building 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 coefficient, water absorption coefficient, and moisture storage. These values were further used as input data to characterize the material properties in the *Delphin* simulation program.

Laboratory data were determined using a series of tests. Depending on the test, three to twenty-two samples were prepared. In addition to the standard test methods, other methods were also used.

TRNSYS Type 56 (2016) was used to calculate the energy balance of the building. Three scenarios were simulated:

- Baseline: building before both renovations.
- Building with internal insulation on the ground and 1st floor walls.
- Building with additional energy-saving measures (insulation of the basement ceiling and roof, replacement of windows).

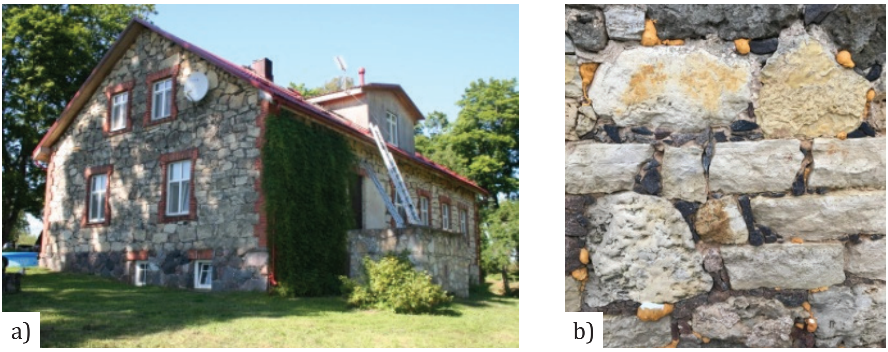

Fig.1.6. Historical building of dolomite stones in *Seces* parish: a) the main facade of the building; b) the outer surface of the stone wall.

All scenario simulations were based on the following assumptions:

- climatic data of Latvia were used;
- indoor temperature +20 °C in zone A2 when the building is used, for example, on weekdays in the morning (6:00 to 8:00) and in the evening (16:00 to 23:00) and full days on holidays, and +18 °C the rest of the time;
- indoor relative humidity 50 %; (4) infiltration 0.05 h^{-1}, with additional natural ventilation during window opening for zone A2 – 0.5 h^{-1}; (5) heat gains are based on values defined in EN ISO 13790:2008, all heat gains are planned.

In December 2017, temperature, relative humidity, volumetric water content and heat flow sensors were installed on the outer walls of the northeast facade. One set of sensors was mounted on the wall of the living room and the other on the wall of the bathroom. Both walls were modernized in 2015 (see Fig. 1.7).

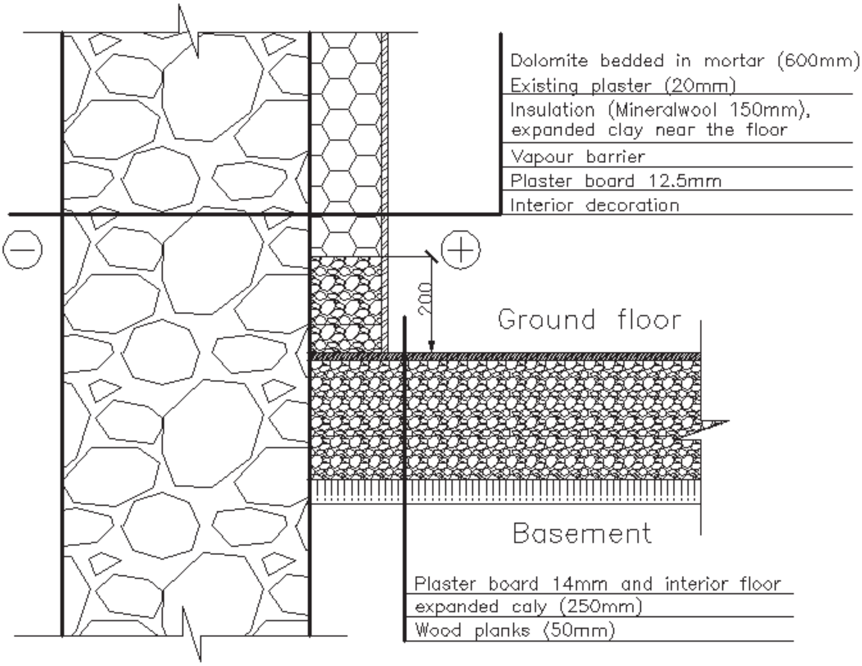

Fig.1.7. Residential rooms – cross section of external walls and floors after the 2015 renovation.

A pyranometer was installed, *Campbell CMP3 060271,* with a sensitivity of 11.72×10^{-6} [V/Wm $^{-2}$] on the northeast facade. The installation of the sensors for the living room and the bathroom is the same, except for the solar radiation sensor. One solar radiation sensor was installed 5 m above the ground level. Indoor temperature measurements were made with twisted pair T-type thermocouples – *Labfacility XE-2342*. Temperature sensor t1 measured the temperature between the dolomite wall and the insulation layer, and t2 measured the temperature between the insulation layer and the vapour barrier. These sensors were installed at a height of 1.8 m from the floor, which corresponds to 4 m from ground level. RH1-2 measured relative humidity in the same places as the temperature sensors. The RH accuracy of *Honeywell HIH-4000-002* measurements was ±3.5 %. The heat flow in the walls was measured with *Hukseflux* heat flow sensors. Volumetric water content was measured using the time domain (TDR) reflectometer *Campbell CR616,* with an accuracy of ±2.5 % of volumetric water content (VWC) and an operating temperature of 0 °C to 70 °C. The CR616 is mounted 3.5 m above ground level. Three data loggers were used to record data: two *Campbell Scientific CR1000* data loggers (one in the living room, one in the bathroom); one *Campbell Scientific CR800* data logger (external). All measurements were performed over a period of 30 minutes. The data from data loggers were collected periodically.

The *Delphin* simulation tool's version 6.1 and the Glazer method were used to evaluate the hygrothermal behaviour of the external walls of the building with internal insulation. The *Delphin* software is a simulation program for homogeneous layers to model heat and moisture mass transport and storage in materials. Glazer's method is used to determine the conditions in different wall layers under specific indoor and outdoor conditions. The simulation used the climatic data entered by the software user. For indoor boundary conditions (temperature and relative humidity), the data obtained from in-situ measurements were used. Weather data such as outdoor temperature, relative humidity, wind speed and direction, hourly rain amount and air pressure were taken from the weather station *Skriveri*, located 20 km from the case study building, while solar radiation data were taken from the weather station at the University of Latvia located 100 km from the case study building. Both meteorological stations are operated by SLLC "Latvian Environment, Geology and Meteorology Centre". The properties of plasterboard and mineral wool materials were imported from the *Delphin* material database. A vapour barrier (S_d = 2.3 m) was added as a resistance between the material layers. The dolomite properties were imported into the model as a new material file using the values obtained during the laboratory tests. However, it should be taken into consideration that the supporting part of the wall is made of heterogeneous natural materials. This was also shown by the results of laboratory tests during this study.

The second study was conducted in a three-story residential building with an additional attic floor and one underground floor [13]. The building was built in 1880 and is located in the historical centre of Riga, approximately 150 m from the Daugava (see Fig. 1.8). The area of the building is 120.9 m^2 with a building volume of 1511 m^3. The building has two adjacent buildings – one on the northwest (NE) side of the building and the other on the northeast (NE) side of the building. Both adjacent buildings are one story taller than the case study building. The southwest (SW) side of the building is the main facade, with an entrance from the street. The SE-facing facade is the largest open area for outdoor weather such as wind-driven rain, solar radiation and wind. The free space between the SE facade and the next building in this direction is 15 metres, this adjacent building has the same height as the case study building. About 10 years ago, the owner of the first-floor apartment installed internal insulation of glass wool (0.05 m) on the SE wall.

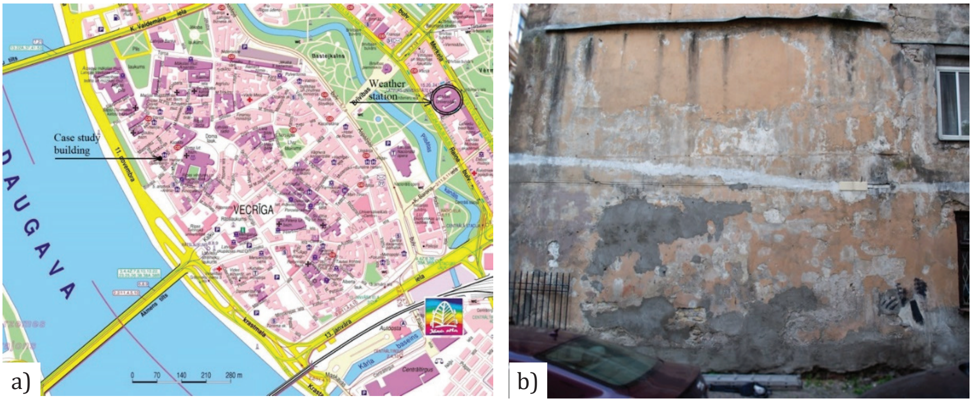

Fig. 1.8. Historic brick building in Old Riga: a) location; b) southeast facade.

Qualitative and quantitative methods were used to determine the possible sources of moisture in the masonry of external walls. Qualitative analysis involves direct observation of the building to identify existing signs of decay and moisture damage. The quantitative method involves the assessment of moisture distribution in the relative scales of the external walls of the building. The moisture content of the wall was measured from the outside. Wall moisture measurements from the inside were limited due to internal insulation. Moisture assessment was carried out at two depths – 2 cm and 20 cm deep in the masonry (including plaster). A multifunctional measuring device, *Trotec T3000,* was used for these measurements. *Trotec T3000* was used with two types of measuring probes for different measuring depths: dielectric probe *TS 660 SDI* for the 2 cm depth; microwave probe *TS 610 SDI* for the 20 cm depth. Both dielectric and microwave probes were used for moisture distribution measurements on a relative scale and could not be directly compared to each other. For monitoring purposes, the measured southeast facing wall was divided into smaller squares to form a grid, each approximately 0.4 m by 0.4 m. The same grid was used for repeated humidity measurements over a period of time.

The wall moisture measurements were started in autumn (September 21, 2018) and continued until spring (March 5, 2019). During the monitoring period, the humidity of the walls was measured 5 times. The monitoring system started collecting data on November 20, 2018. The monitoring system included the monitoring of relative humidity and temperature between the outer wall insulation layers. The relative humidity and temperature monitoring between insulation layers was performed using a *Honeywell HIH 4000-002* and a T-type PFA insulated double twisted pair thermocouple cable. The *Campbell CR1000* data logger was used to record data from these sensors. A small hole with a diameter of 27 mm was drilled in the internally insulated wall to insert the monitoring system. In total, two relative humidity and two temperature sensors were installed in the insulation layers. The sensors were installed in pairs (the relative humidity sensor together with the temperature sensor). Pairs of sensors were installed 20 cm below the hole, one pair between the wall and the insulation and the other pair between the insulation and the plasterboard. In addition, the temperature and relative humidity at the inner surface of the insulated wall were measured. After placing the relative humidity and temperature sensors, the hole was re-filled with mineral wool and plasterboard. To avoid adding additional moisture to the insulation system through the cut and to maintain access to the sensors, no plaster was used to cover the hole. Instead, the plasterboard was sealed with a masking tape and additionally covered with a vapour-tight aluminum tape. Weather data from the nearest meteorological station was used. The meteorological station is located at the University of Latvia, and the data is managed by the Latvian Centre for Environment, Geology and Meteorology.

1.4. A block of positive energy balance in a historic urban environment

Historically built structures carry many layers and dimensions of nationally and globally important cultural values. Therefore, the task of transforming the historical city block into a positive energy balance block is as complex as the construction volume of the city itself. The methodology of this research is organized in six consecutive stages: the block selection, an evaluation of energy efficiency potential, data analysis, identification and selection of planned measures, evaluation, and conclusions [14]increasing usage of RES and decreasing the carbon footprint. There are stringent requirements for new buildings, but the energy efficiency potential in the existing building stock is still not fully explored. The latest trend in urban energy efficiency is the Positive Energy Block (PEB. The decarbonization strategy of the city block of the historical centre through the concept of a positive energy balance block was developed taking into consideration two aspects – energy efficiency and cultural heritage. At each stage of the research methodology, the perspective of both parties was taken into consideration. Typically, energy efficiency scenarios are weighed using the cost-benefit analysis and the CO_2 life cycle analysis. In this study, the assessment is supplemented with an assessment of the impact of energy efficiency measures on cultural heritage. Increasing comfort in historic buildings and adding new elements is considered trespassing. For further discussion, it is important to evaluate whether the proposed project increases the quality of life in the city block and what is its impact on the values of the historical heritage. Three different assessment analysis methods illustrate different possible perspectives and serve as a basis for discussion among professionals (environmental engineers, architects, local urban planners and authorities) and the general public on how to find a balance in climate change. mitigation measures and cultural heritage conservation towards a low carbon society.

As part of the research, a methodology for selecting the city block with the greatest potential to achieve a positive annual energy balance has been developed and used. It is applicable to any densely built-up urban environment. The aim of the first step of the study is to select a block for smart urban regeneration. Since the research has two equally important goals, the selection of the block is considered from two perspectives – its energy efficiency potential and high quality of *Baukultura* and habitability in the city block. The selection of the quarter was based on a multi-criteria analysis, where possible alternatives were evaluated according to the set of criteria important to the objective [15], [16]. The study was conducted in three stages (see Fig. 1.9).

PHASE 1

CONTEXT AWARENESS, GOAL SETTING

Target identification

PHASE 2

CHOOSING ALTERNATIVES FROM DIFFERENT PERSPECTIVES

Interested person

- Multi-criteria analysis according to a specific sub-goal "Energy efficiency"
- Multi-criteria analysis according to a specific sub-goal "Cultural heritage and viability"
- Multi-criteria analysis according to a specific sub-goal "Investments"
- Multi-criteria analysis according to a specific sub-goal "Municipal development prevention"

PHASE 3

COMPARISON OF RESULTS AND DECISION MAKING

Conclusions

Fig. 1.9. Research methodology.

At the beginning, the decision-making context is identified, goals are set, and a decision-making hierarchy is established. Then, according to the number of stakeholders involved, several sets of multi-criteria analysis methods are developed. This study examines energy efficiency and cultural heritage and viability. The alternatives are ranked according to the sub-goals of each analysis, and the best alternative for each stakeholder is determined. At the end, the results are compared and final decisions are made based on the results of the second step and summarized in the conclusions.

A methodology was created for one of the most complex phases of the study – the phase of selection of measures [17]. The methodology consists of three main phases – initial research, conceptual development, and calculation of the total energy balance (see Fig. 1.10). This research describes step 2 – the initial assessment of the decarbonization potential of the selected city block, including preliminary energy consumption data analysis and evaluation of possible renewable energy concepts.

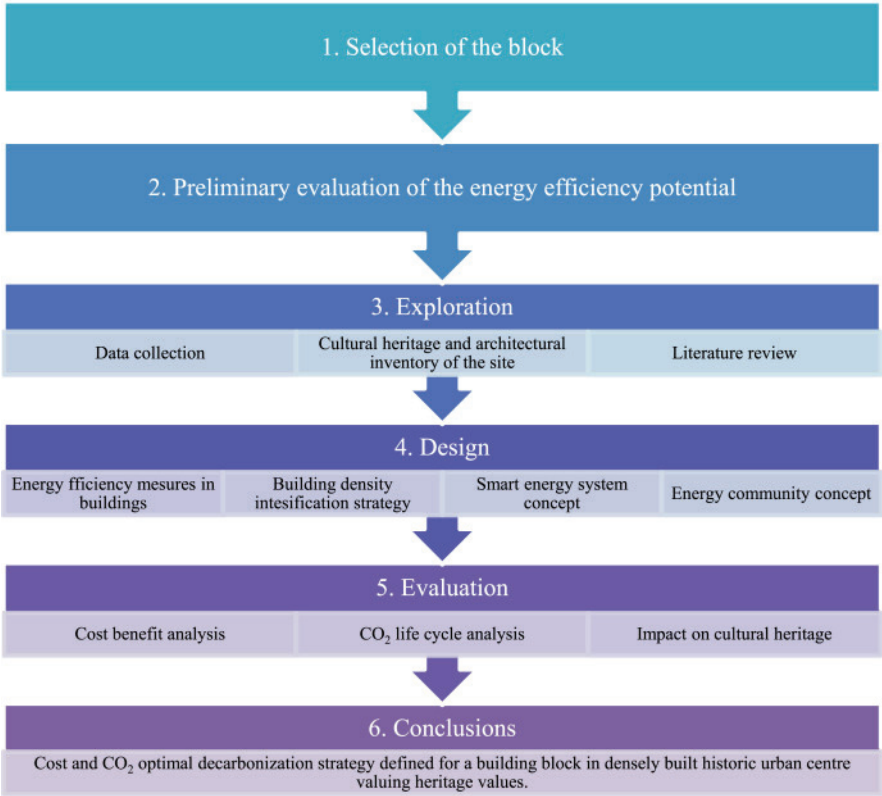

Fig. 1.10. Methodology used in the study.

Data on the current situation were obtained from energy consumers or publicly available databases. In order to estimate the preliminary energy saving potential in the selected city block, a simplified calculation was performed, evaluating 1) the energy saving of the deep renovation of the building; 2) RES production with traditional technologies – PV and solar thermal energy; 3) the waste heat recovery technology.

2. RESULTS

2.1. Materials and constructions of historical buildings

From the results of the *Delphin* simulations, two dominant clusters containing 70 % of all samples (37.5 and 32.5 %) were identified. After cluster merging, these three dominant clusters (B, 3, and 5) formed two new dominant clusters (B3 and B5). In total, 67.5 % of all samples were in these two clusters, 30 % in B3, and 37.5 % in B5.

One sample (18–4) was recognized as the only sample in both cluster groups. Compared to the other brick samples according to their description, there were 3 more bricks with the same description (yellow clay brick, produced in the first half of the 20th century). Three other bricks belonged to group B4, and there was only one brick in this group, which was a red clay brick produced in the 2nd half of the 20th century.

Most of the samples of the combined cluster group B5 were red clay bricks (86.7 %), and most of them were produced between the second half of the 19th century (30.8 %) and the first half of the 20th century (38.5 %). In the second largest cluster group, B3, almost all the bricks were red clay bricks, except for one brick, which was made of concrete, and in this group, most of the bricks were produced in the period from the 19th century (27.3 %) to the first half of the 20th century (36.4 %).

However, it should be noted that most of the brick samples were red clay (75 %), and 60 % were produced in the period from the second half of the 19th century (22.5 %) to the first half of the 20th century (37.5 %).

Looking at the clusters from the *Delphin* results, where 35 out of 40 bricks were in the same cluster, this could indicate that different parameter clusters generate similar results, in this case parameter sets 5 and 4 had a 100 % overlap with the result set B, followed by the parameter set 3 with a 92.3 % overlap and cluster 1 with a 25 % overlap. However, it should be noted that the low number of clusters, in this case 3, from the *Delphin* result data is due to the large distance between the first two cluster combination with 1 and 2 clusters, 494.17 and 378.56, respectively, followed by the distance of 168 in the 3-cluster combination. If the first two cluster combinations are excluded from the calculations of the optimal cluster combination, then the optimal number of clusters versus distance would be a combination with 15 clusters and a distance of 37.5.

Since the input data for P-clusters is based on the numerical simulation output, these results are greatly influenced by the chosen numerical calculation program (*Delphin*) and the input data of the performed simulation (material properties, selected geometry, climatic conditions, boundary conditions, etc.), so the interpretation of the results is limited to the specific climatic conditions and the set of brick samples used in this study [7].

The hygrothermal performance of 40 types of solid masonry walls insulated from the inside with vapour-open capillary-active calcium silicate in cold climates show that all wall types have very similar temperature trends, while there is a large difference in moisture behaviour. This corresponds to the conclusions in [18] that the effect of the brick type on relative humidity and temperature under thermal insulation is complex. The obtained results show that the temperature fluctuations between different types of walls depend on the thermal resistance of the bricks – the higher the thermal resistance, the lower the temperature under the thermal insulation material (see Fig. 2.1).

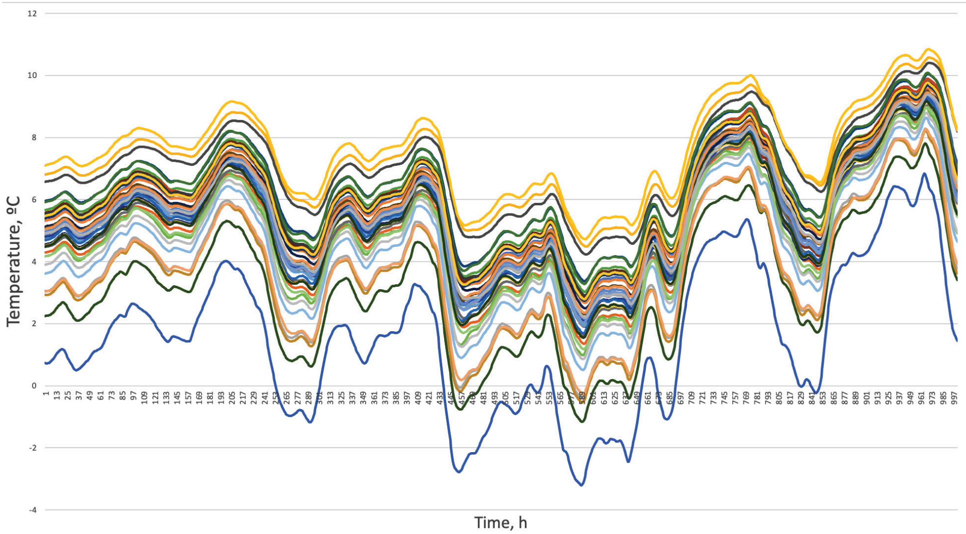

Fig. 2.1. Temperature under thermal insulation at a time stage between 7800 and 8800 hours.

In Fig. 2.2 it can be seen that the moisture content levels differ four times for different types of walls. Also, the distribution of moisture content in the masonry differs significantly: it can be observed both as a constant moisture level in the entire masonry and also as a constant moisture level in the outer part of the wall, followed by a rapid decrease in the deeper layers of the masonry. The data analysis shows that no correlation was found in this study between the moisture content, relative humidity level and other parameters (water absorption coefficient, liquid water conductivity, porosity, density).

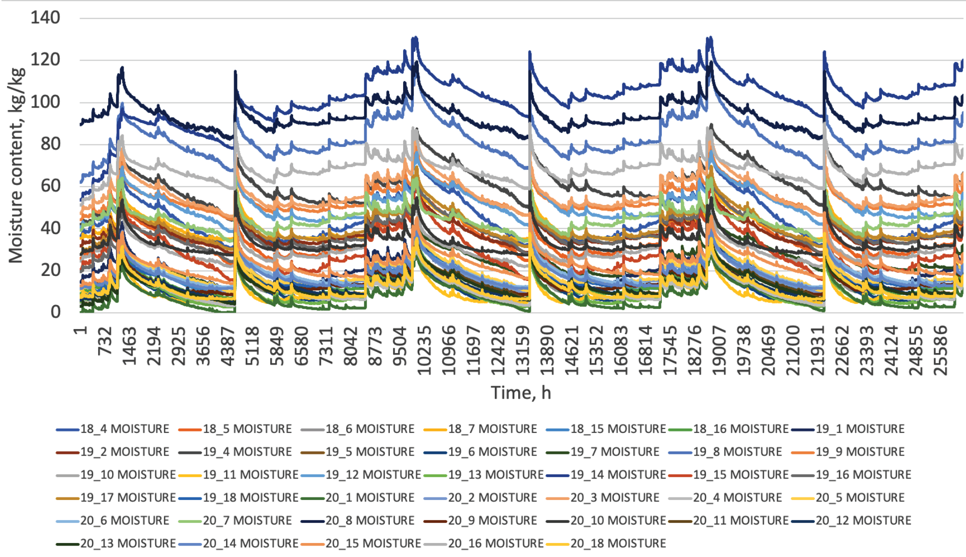

Fig. 2.2. Masonry moisture content for all simulated wall types.

The obtained results cannot confirm the conclusions made in other studies that the hygrothermal performance of massive masonry walls insulated from the inside with vapour-permeable capillary-active materials depends on the distribution of pore sizes, which determines the water conductivity of the brick liquid (the higher this parameter, the deeper rain penetrates the masonry) [19]. It also does not match the conclusions in [18] that the masonry walls with high capillarity have higher relative humidity and temperature indicators. The study did not determine the pore sizes of the material, therefore the results could not be compared with the results in [19] saying that the pore sizes significantly affect the material's hygroscopic properties: small pores mainly increase hygroscopicity (e.g. sorption isotherms), while large pores mainly improve capillarity (e.g. capillary absorption coefficient).

If the construction quality is low and the glue does not ensure full contact between the masonry and the thermal insulation material, rain moisture can penetrate into the thermal insulation material. In Fig. 2.3, an example is shown with masonry made of brick 20_18 with and without glue. If the glue ensures full contact between the masonry and the thermal insulation material, the effect of wind-driven rain on the thermal insulation material is not observed. These findings are consistent with the findings in study [20]. The adhesive has a high moisture buffering capacity when applied correctly. Similar conclusions were drawn in another study [21].

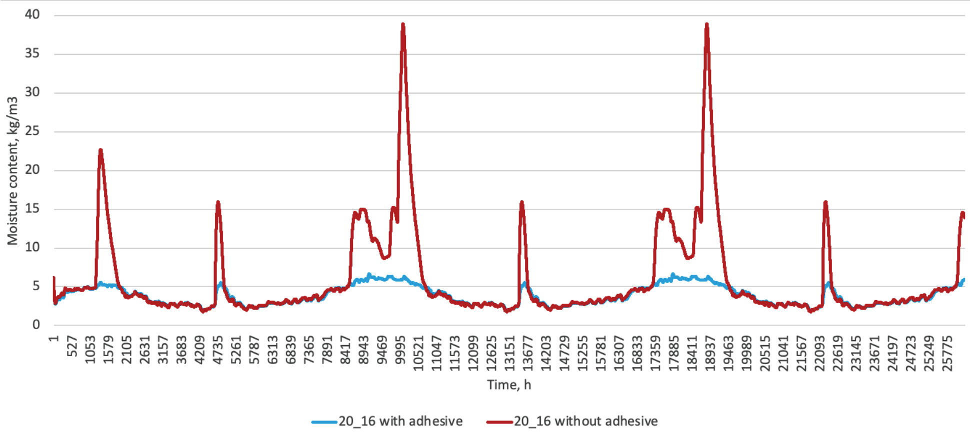

Fig. 2.3. Moisture content of thermal insulation material brick 20_18 masonry with and without glue.

The simulation results show that when internal thermal insulation with capillary-active calcium silicate is used in cold climates with normal indoor humidity loads, the relative humidity does not exceed 96 % and is considered safe [22]. This conclusion applies to thermal insulation with and without glue.

2.2. Thermal insulation materials and systems

The obtained results show that there is a discrepancy between the measured and simulated hygrothermal behaviour. The test results show that the relative humidity growth rate between the masonry and the thermal insulation material is high in the first days of the test for all materials and slows down as equilibrium conditions are approached. The temperature decreases at a slightly slower rate than the relative humidity and reaches equilibrium in about 5 days. The simulation performed prior to the experimental test showed a much lower rate of increase in relative humidity and the rate of decrease in temperature compared to the measured behaviour. The correlation analysis between the measurement and simulation results in Fig. 2.4 shows that there is a close relationship between the temperatures – the correlation coefficient R^2 is in the range from 0.81 to 0.86. There is a close correlation for the relative humidity of wood fibres ($R^2 = 0.84$), but much weaker for EPS ($R^2 = 0.59$) and mineral wool ($R^2 = 0.54$).

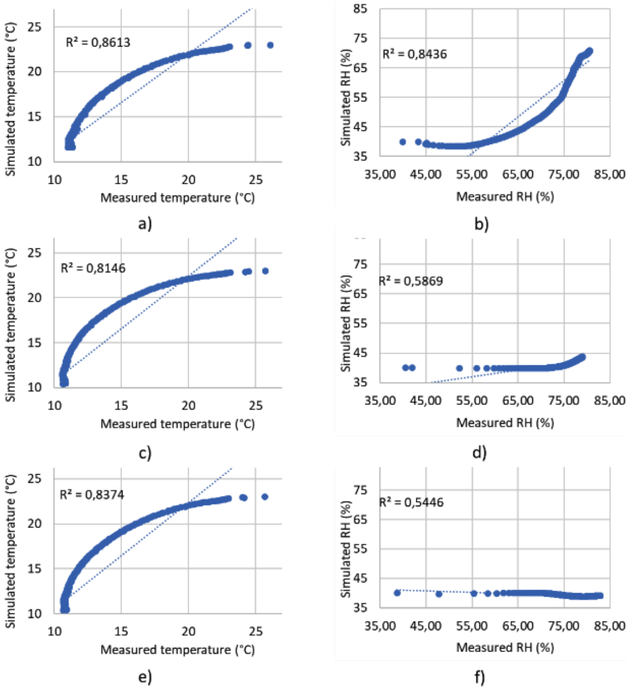

Fig. 2.4. Correlation between the modelled and measured temperatures between the masonry and the insulation layer: a) wood fibre; c) EPS; e) mineral wool) and relative humidity: b) wood fibre; d) EPS; (f) mineral wool).

The fit of the model to the measured data was improved using parametric analysis. This was done by changing the parameters of masonry, mortar and insulation materials. Thermal conductivity, dry material density and water vapor diffusion resistance coefficient of the insulation materials were changed to the values specified by the material manufacturers. Specific heat capacity, water conductivity at saturation, water absorption coefficient, and initial relative humidity were corrected for brick and mortar thermal conductivity. The corrected values are shown in Table 2.1.

Table 2.1

Properties of Materials Used for Parametric Analysis

		A brick	Mortars	Mineral wool	Wood fibre	EPS
Name of the material in the Delphin database		Old brick building Dresden NW	Lime cement mortar	Mineral wool	Wood fibre insulation board	Polystyrene plate – expanded
Density of dry material, kg/m^3		1619.51	1878.47	28 (–24 %)	50 (–67 %)	13.5 (–41 %)
Thermal conductivity, W/mK		0.482 (+20 %)	0.5 (–38 %)	0.036 (–10 %)	0.038 (–10 %)	0.039 (+8 %)
Specific heat capacity of dry material, J/kg		430 (–55 %)	470 (–38 %)	840	2000 years	1500
Water vapour diffusion resistance coefficient		10.4726	36.9113	1	2.1 (–30 %)	30 (–69 %)
Water absorption coefficient, $kg/(m^2 \cdot s^{0.5})$		0.423587 (+11 %)	0.211622 (+486 %)	0	0.07	0.00001
Effective saturation (long-term process), m^3/m^3		0.761043 (+111 %)	0.1 (–55 %)	0.9	0.6	0.92
Conductivity of liquid water at effective saturation, s		0.259E –10 (+24 %)	3.52E –10 (+3339 %)	0	0.0216E–10	0
Sorption isotherm	Moisture content, m^3/m^3 RH 0 %	0.004030	2.83E-08		0.0000683	0.0000528
	RH 30 %	0.007003	0.004542		0.0048476	0.000455
	RH 50 %	0.007261	0.015729		0.0080606	0.000617
	RH 80 %	0.007720	0.027090		0.0176992	0.001078
	RH 95 %	0.023461	0.037559		0.0328964	0.009227
	RH 100 %	0.761043	0.1		0.6	0.92
Initial relative humidity in the material, %		65 (+62 %)*	85 (+112 %)*	40	40	40
Initial temperature of the material, °C		23	23	23	23	23

* inside the material starting at a depth of 2.5...3.5 cm from the outer surfaces of the material

The study [11] concluded that the accuracy of the material parameter values and the initial values of the materials play an important role in the simulation, but the initial values have a much greater impact.

The performed parameter analysis showed the parameters that most significantly influence the hygrothermal behaviour of the structure. The parameters of all three thermal insulation materials used in the test were adjusted to the values provided by the material manufacturers: thermal conductivity increased by 8 % for EPS and decreased by 10 % for mineral wool and by 10 % for wood fibre. The density was reduced for all three insulation materials – to 24 % for mineral wool, 67 % for wood fibre, and 41 % for EPS. The water vapour diffusion resistance coefficient was reduced for wood fibre by 30 % and for EPS by 69 %.

In order to bring the simulation results closer to the measurement results, the thermal behaviour was changed, increasing the thermal conductivity of bricks by 20 %, and reducing it by 38 %. The specific heat capacity was significantly reduced for bricks (55 %) and mortar (38 %).

The initial relative humidity of the material has the greatest effect on the growth rate of moisture transfer: it was increased by 62 % for bricks and by 112 % for mortar compared to the pre-test simulation values. The masonry was dried for 10 days before the tests, which was too short a period of time to dry out, so the moisture level at the start of the tests was still higher than predicted during the pre-test simulation. Another parameter affecting the moisture transfer is water conductivity at effective saturation, which was increased by 24 % for brick and mortar, resulting in an increase in water absorption coefficient of 11 % for brick and 486 % for mortar. Effective saturation was increased by approximately 111 % for brick and decreased by 55 % for mortar.

Figure 2.5 illustrates the changes in temperature and relative humidity during the simulation before and after the experiment and measurement results for a fibreboard wall without a vapour barrier. The main difference between the measured and the pre-test simulation temperature was observed in the first 10 days, when the pre-test simulation temperature decreased more slowly than the measured temperature. After the test, the simulation results are in good agreement with the measured temperatures. The temperature in the steady state differs by only 0.6 °C. To achieve acceptable results after the test simulation for compliance, the values of thermal conductivity, dry material density, and specific heat capacity have been changed. The same trend was observed for relative humidity: the pre-test simulation had a much lower growth rate at the beginning, so it had not reached equilibrium during the simulation period. After the test, the simulation and measured relative humidity correlate well, and both stabilize at about 80 %. To achieve similar post-test results to the simulation, the water vapour diffusion resistance coefficient, water conductivity at effective saturation, the water absorption coefficient and the initial relative humidity of brick and mortar have been varied.

The test results show that under equilibrium conditions, the highest relative humidity between the masonry and thermal insulation is achieved by mineral wool (82.9 %), followed by wood fibre without a vapour barrier (80.5 %), EPS (79 %), aerogel with a vapour barrier (78.2 %), aerogel without vapour barrier (73.3%) and wood fibre with a vapor barrier (72.7 %). The temperature between the masonry wall and all insulation materials has stabilized on average at +10 °C.

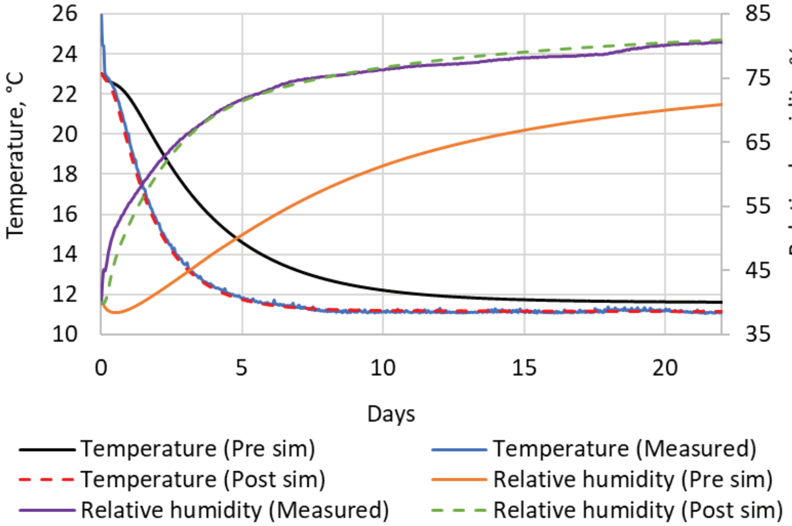

Fig. 2.5. Temperature and relative moisture behaviour between the masonry and fibreboard without steam barriers: simulation before and after the experiment and measurement results.

The relative humidity has not increased above 95 % (the condition when capillary saturation begins) in any of the materials, so there is no risk of freezing. This can change if the external boundary conditions are changed, such as wind-driven rain and solar radiation at the surface. However, there is a risk of mould formation for insulation materials of biological origin, such as wood fibres, as was observed during the tests.

In study [10], a test was conducted with 18 thermal insulation systems, but the temperature and relative humidity sensors were damaged in the gypsum plaster system at the beginning of the test, so the measurement data of 17 thermal insulation systems are used in the analysis of the results.

The obtained results show that insulation from the inside has a great impact on the hygrothermal behaviour of the wall, as the relative humidity between the thermal insulation and the masonry wall increases, which, in turn, increases the risk of mould growth, frost damage, and the collapse of wooden beams.

The tested thermal insulation systems have similar thermal behaviour but different moisture behaviour. Figure 2.6 illustrates the simulated and measured temperature between the thermal insulation material and the masonry wall during the equilibrium cycle for eight thermal insulation systems.

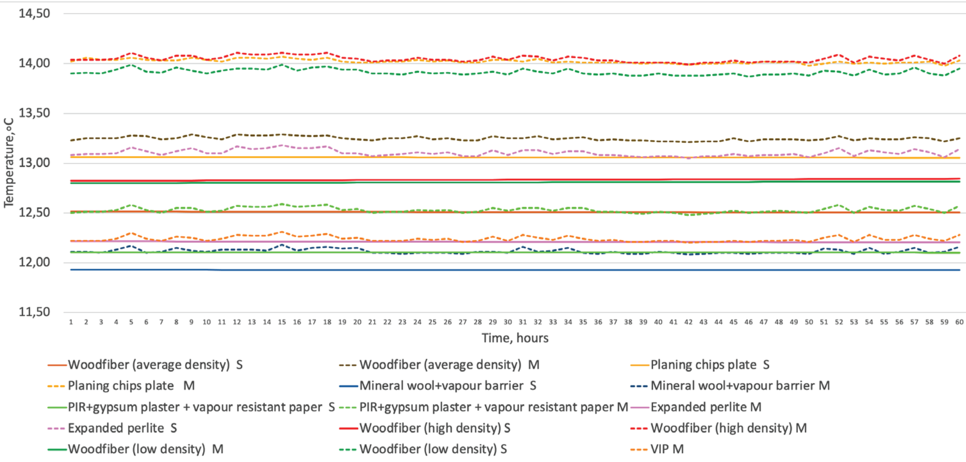

Fig. 2.6. Simulated (S) and measured (M) temperature between the thermal insulation material and the masonry wall in the equilibrium cycle (time period between 245 and 305 minutes).

The delay resulting from the heat flow between the inner surface and the outer surface of the structure can be observed in all thermal insulation systems (see Fig. 2.7). The average time shift in the steady state depends on the boundary conditions. The greater the difference between indoor and outdoor temperatures, the greater the time lag. The temperature reduction coefficient, which reflects the ratio of the amplitudes of the heat flow waves, differs for different thermal insulation systems and is positively correlated with the vapour diffusion resistance.

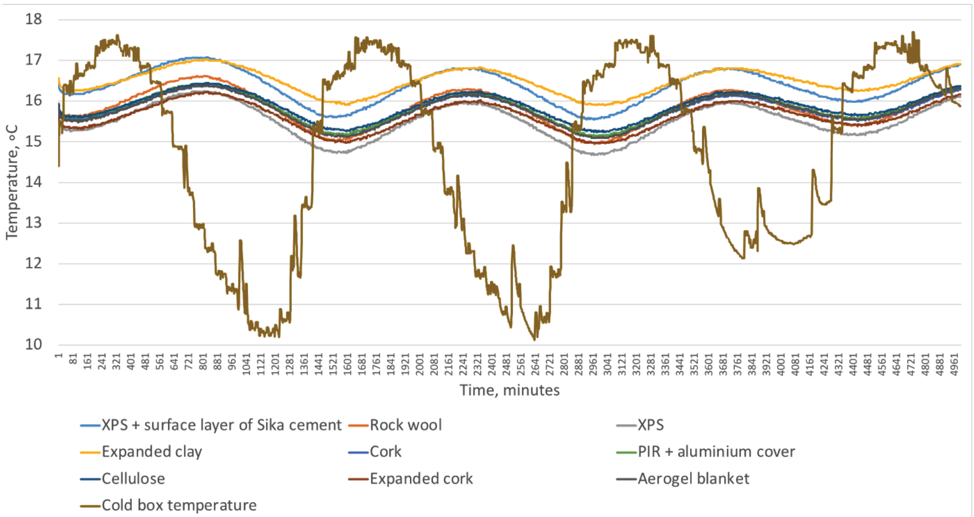

Fig. 2.7. Temperature changes between the masonry and the thermal insulation material in the dynamic test.

The relative humidity under the insulation material is affected by changes in outdoor air temperature and indoor relative humidity. If the outdoor temperature is constant and the indoor relative humidity fluctuates under environmental conditions, the relative humidity under the insulation in vapour-permeable thermal insulation systems with low vapour diffusion resistance behaves like the indoor relative humidity (see Fig. 2.8). The delay depends on the values of S_d. The smaller the vapour resistance, the smaller the time delay for the propagation of the relative humidity wave from the outer surface of the wall to its inner surface, and the greater the ratio of relative humidity wave amplitudes on both wall surfaces. Vapour-tight systems with high vapour diffusion resistance are not affected by the indoor relative humidity, and the relative humidity between the masonry and the thermal insulation depends only on the outdoor air temperature.

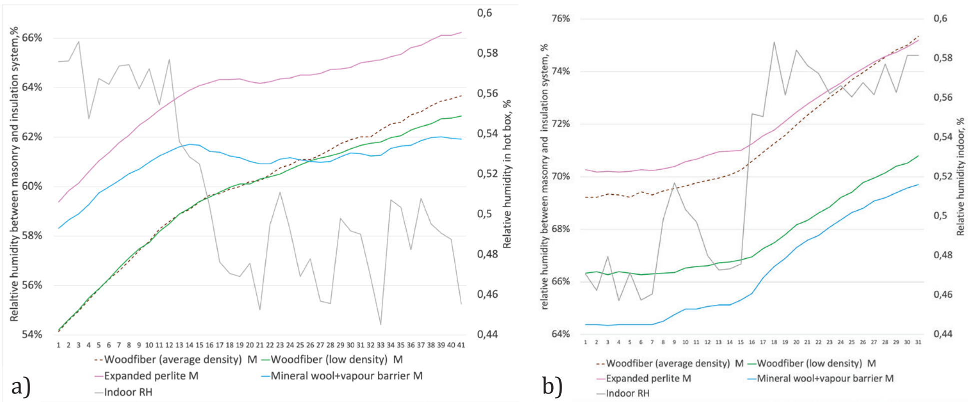

Fig. 2.8. Changes in relative humidity between the masonry and vapour-permeable thermal insulation material when the relative humidity of the room a) decreases and b) increases.

If the indoor relative humidity is stable and the outdoor temperature fluctuates, in vapour-permeable thermal insulation systems with low vapour diffusion resistance, the relative humidity under the insulation follows the temperature profile. The lower the vapour diffusion, the more closely the relative humidity waves under the insulation follow the temperature profile. For vapour-tight systems, the range of relative humidity values decreases as the vapour diffusion resistance decreases. Figure 2.9 shows how the relative humidity changes between the thermal insulation and the masonry if the indoor relative humidity is stable and the outdoor temperature fluctuates.

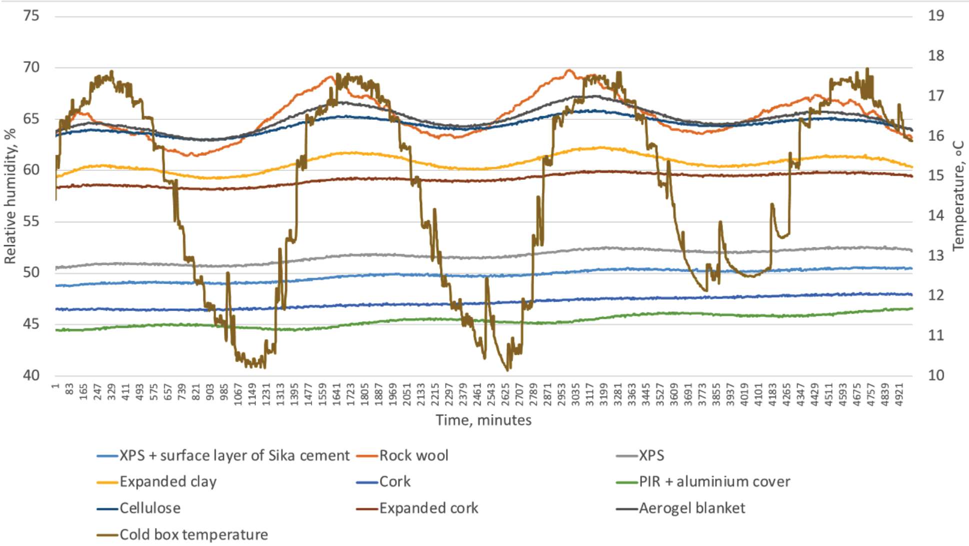

Fig. 2.9. The relative humidity between the thermal insulation and the masonry when the indoor relative humidity is stable and the outdoor temperature fluctuates (dynamic cycle).

When indoor relative humidity and outdoor air temperature fluctuate, the vapour-permeable systems with low vapour diffusion resistance more closely follow the indoor relative humidity profile.

In Fig. 2.10, the wind-driven rain test results for nine thermal insulation systems are shown. The results show that the increase in relative humidity under the thermal insulation systems during wind-driven rain is related to the vapour diffusion resistance of the material. The greater the resistance, the greater the effect of wind-driven rain, reducing the chance of drying to the room side.

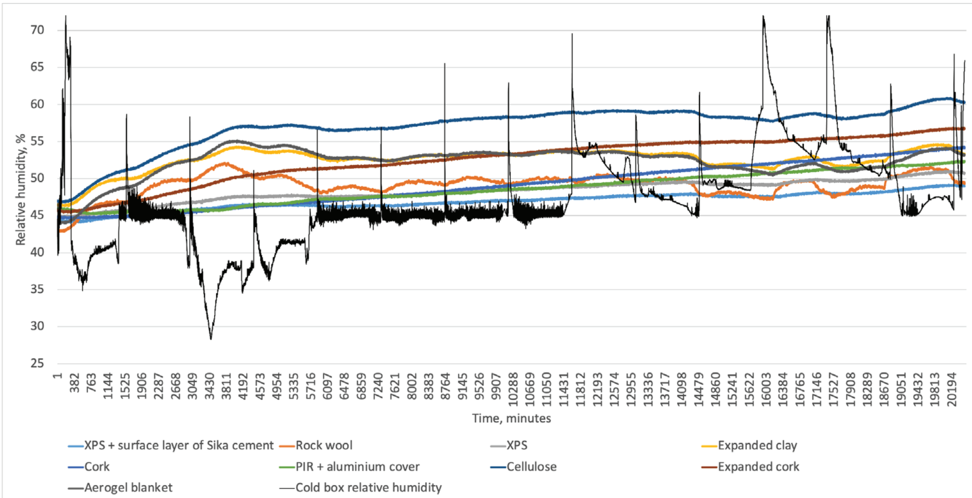

Fig. 2.10. Wind-driven rain test results for nine thermal insulation systems.

Vapour-permeable materials such as cork, blown cork and high density fibreboard without vapour barriers perform similarly to vapour barrier systems. The relative humidity under insulation is less sensitive to changes in indoor relative humidity and more sensitive to changes in outdoor temperature. Cork is less sensitive to moisture than wood and wood materials.

The study shows that the testing period should be longer to determine the moisture accumulation in the masonry samples and its effect on the temperature and relative humidity under the insulation material. In order to determine the long-term effects of moisture accumulation, it is necessary to perform either longer test cycles or simulation of the mathematical model, validating the model with already obtained short-term data.

Numerical experiments in the *Delphin* simulation tool showed that the quality of the simulation depends on the input data. In order for the simulation to provide the most accurate input data, all materials, including thermal insulation and grout, should be as close as possible to actual values. Materials should be tested before simulation, and a custom material file should be created for each to make the simulation as close to reality as possible. Other studies have similar conclusions [20], illustrating the importance of brick parameters – two bricks with a similar water absorption coefficient have different water conductivity and hygrothermal behaviour. Kloseiko etc al. in [23] concluded that internal insulation projects still require a case-specific approach. Another study finds that many material parameters required for hygrothermal simulations are difficult to determine, in particular vapour conductivity and capillary conductivity as a function of moisture content [24]. On the other hand, Leone et al. in [25] recommend detailed planning to obtain all parameter values required for each internal insulation project.

Within the framework of this research, an innovative insulation material of biological origin from pine (*Pinas Sylvestris*) needles, produced according to bioeconomy principles, and its use for internal insulation of historic massive walls were also examined [26]. The study was conducted to determine the hygrothermal properties of the material and to evaluate the effect of temperature and relative humidity on moisture transport and accumulation, as well as the critical conditions for mould growth. The needle insulation material was treated with lime to prevent the mould growth and was compared with untreated material. The innovative biologically produced material was prepared based on bioeconomy principles and with a reduced life cycle impact. This high added value product was created from pine needles from forest residues. The needles were mixed with lime and xanthan gum to avoid the use of fossil-based products with a high environmental impact.

The obtained results show that the studied material is very porous and the addition of lime increases the moisture absorption rate of the material due to the increase in the pore area. Needle thermal insulation material has a higher moisture transfer and storage capacity and is a good hygroscopic regulator. This is an important feature of the thermal insulation material used for the internal insulation of historic buildings because it can dry quickly when the relative humidity of the surrounding air decreases. Treatment of thermal insulation material with lime has a small effect on thermal conductivity but has an effect on the reduction of mould growth (see Fig. 2.11).

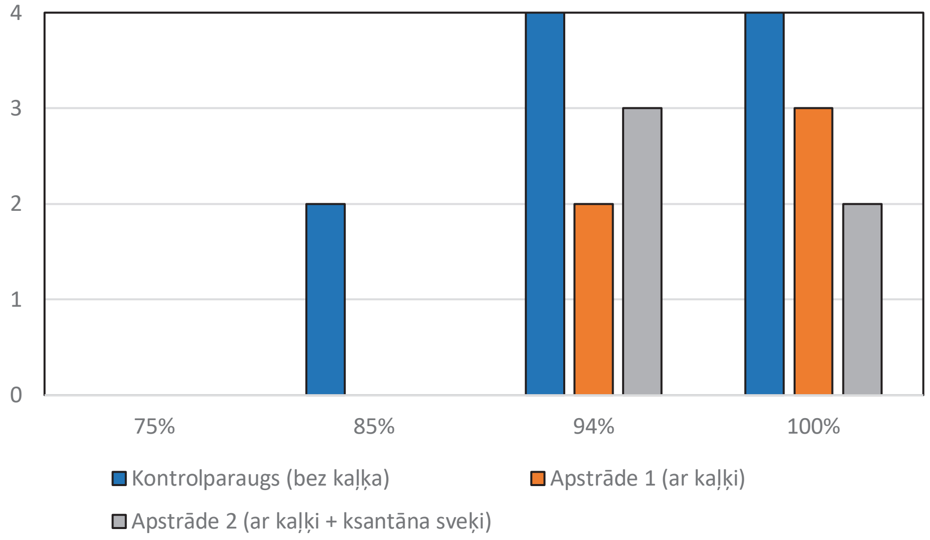

Fig. 2.11. Mould growth on material samples under different relative humidity conditions (blue – control group; orange – with lime; gray – lime + xantan).

No mould formation was observed in the lime-treated sample at 85 % relative humidity, while at 94 % and 100 % relative humidity values, mould was found in all samples (see Fig. 2.12).

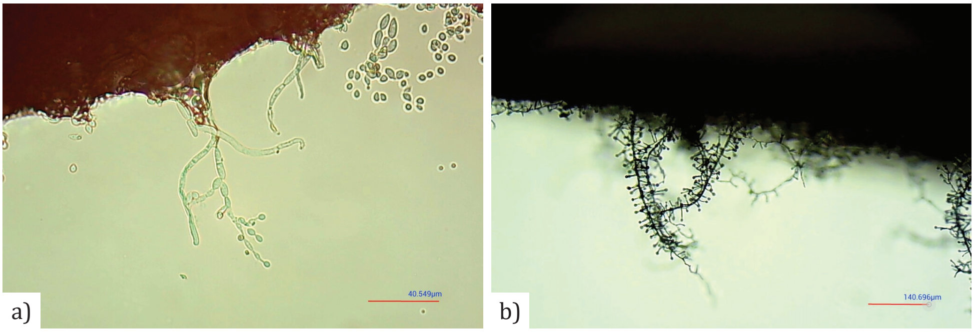

Fig. 2.12. Mould formation on samples at 100 % relative humidity: a) *Cladosporium* on the sample surface without lime; b) *Trichoderma viride* on the surface of the treated sample.

At equilibrium, the lower temperature results in a higher level of relative humidity between the stone wall and the needle insulation material and reaches the critical value for mould growth. The results of the dynamic conditions test (see Fig. 2.13) show that the main driving force of the change in relative humidity is the relative humidity of the indoor air and not the temperature change in the wall. Even if the thermal insulation material is treated with lime, it is necessary to sacrifice heat savings to reduce the critical conditions for mould growth.

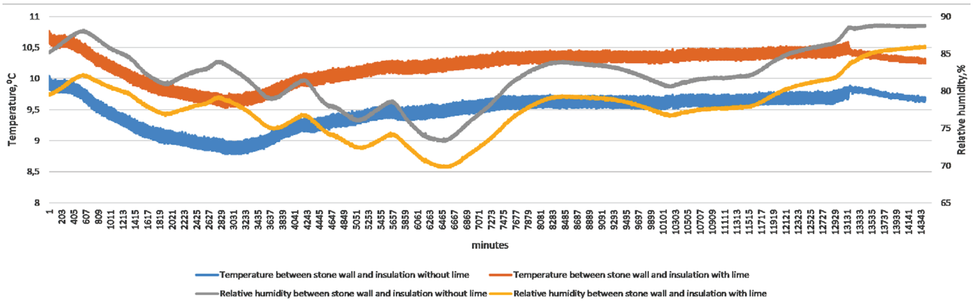

Fig. 2.13. Relative humidity and temperature under varying conditions between the stone wall and needle insulation with and without lime.

The study concludes that future research should focus on optimizing the weight ratio of lime to insulation material to improve the hygrothermal behaviour and critical conditions for risk modes. Additional tests must be carried out to reduce the compaction of the insulation material in the wall. Other materials to reduce lime dusting should be tested.

2.3. The use of internal insulation in historic buildings

In a single-family house in *Sece*, in-situ measurements and hygrothermal simulation in both rooms showed satisfactory hygrothermal conditions in the wall [12]. The hygrothermal behaviour of the outer wall showed that there is no risk of mould growth, because under normal operating conditions of the building (except for water leakage accidents), the relative humidity between the thermal insulation layer and the plasterboard is relatively low (below 60 %). Figure 2.14 shows the measured relative humidity changes in the room, in the outdoor air, and under the thermal insulation, as well as the simulated relative humidity values in the living room.

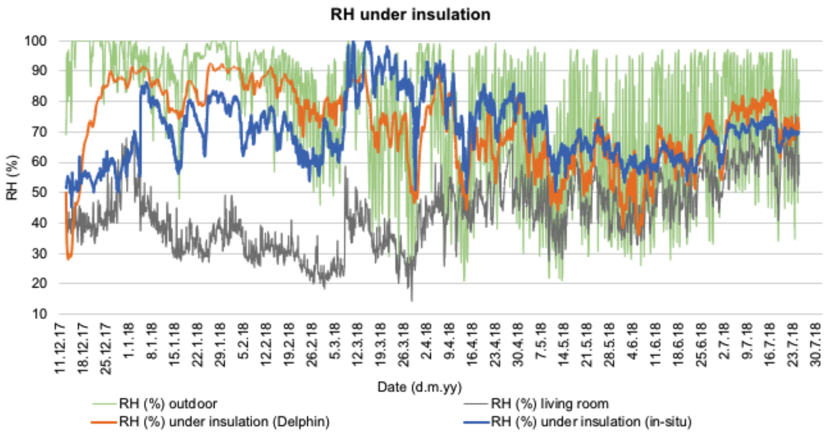

Fig. 2.14. Measured and simulated relative moisture changes in the room and under the insulation.

Figure 2.15 shows the measured relative humidity changes in the room and under the thermal insulation, as well as the simulated relative humidity values in the bathroom.

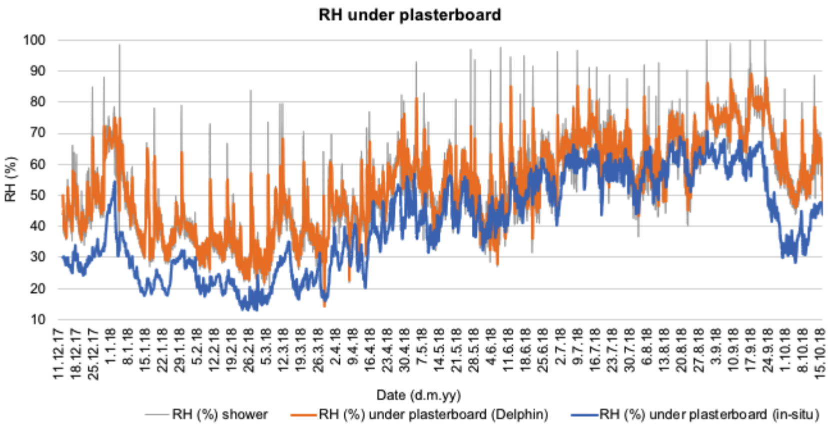

Fig. 2.15. Changes of relative moisture in the room and under thermal insulation and simulated relative moisture values in the bathroom.

The relative humidity above the critical 80 % between the dolomite wall and the insulation layer is only reached for a short time. But at these times and in this location, the temperature is lower than necessary for spore germination (initial mould growth). Mould formation can occur at 80 % high relative humidity if the temperature is at least 20 °C for porous materials. However, given that the tenants found mould on the bathroom walls during the 2015 renovation, there is potential for mould growth if the right conditions (high relative humidity and temperature) occur and persist long enough, because the wall materials contain mould spores.

Temperature measurements indicate that the outer portion of the dolomite wall experiences repeated freeze-thaw cycles, but the risk of collapse from freeze-thaw cycles is extremely low because the dolomite does not reach its saturation point.

The simulation results show that the annual heat consumption for space heating in the base scenario can be reduced by 35 % if the ground and the first-floor walls are warmed from the inside. If a significant increase in energy efficiency is carried out (insulation of internal walls, basement ceiling, roof insulation, replacement of windows), the basic energy consumption can be reduced by 72 %. The actual energy consumption is calculated based on the data provided by the residents who calculate the primary energy resources – firewood, which is partly supplied directly from the forest and dried on site. If the consumption of wood logs is converted into final energy, the annual energy consumption per heated area should be 87 kWh/m^2. Energy savings are 17 % less than calculated in the simulation model. This difference can be caused by several reasons, such as uncertainty about the quality of the construction work and remaining thermal bridges, model inputs, including the factors related to the frequency of occupancy (heat gain, room temperature, and ventilation frequency). The simulation results are sensitive to the quality of input data such as room temperature, relative humidity, ventilation, and material properties. Historical buildings lack detailed information about wall cavities, the ratio and typology of stone and mortar, construction defects, and the specific properties of materials. On the other hand, the uncertainty of the actual primary energy consumption, including the amount and quality of firewood efficiency of energy conversion technologies, significantly affects the final energy consumption values.

The historical building in *Bīskapa Gāte* in Riga was found to have significant damage to the plaster of the facade, and the building has many cracks and gaps on the facade. These open areas provide outdoor humidity, including penetration of wind-driven rain into exterior walls. Based on the analysis of weather data, the study concludes that the facade is strongly influenced by outdoor relative humidity and rain. Algae growing on the facade shows that there has been rainwater on the surface of the walls. The weather data show that the prevailing wind during the monitoring period is from the southeast and the largest facade of the building is exposed to wind-driven rain. Figure 2.16 shows the temperature measurements during the monitoring period. The temperature in the room and the temperature between the wall and the thermal insulation follow the outdoor air temperature profile because the room has insufficient heating radiator capacity.

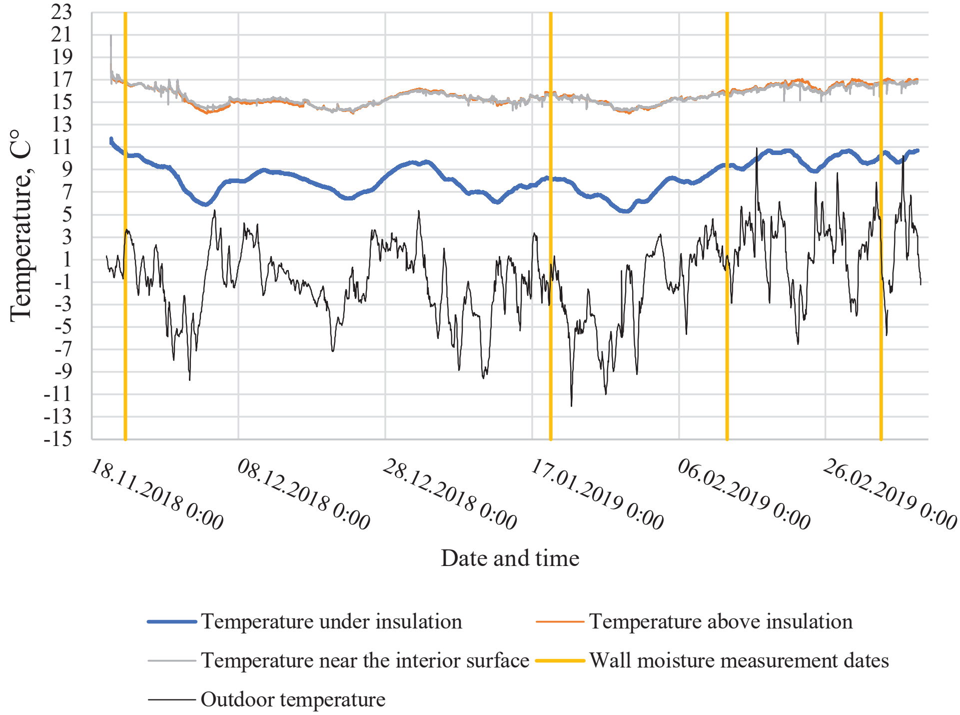

Fig. 2.16. Temperature measurements during the monitoring period.

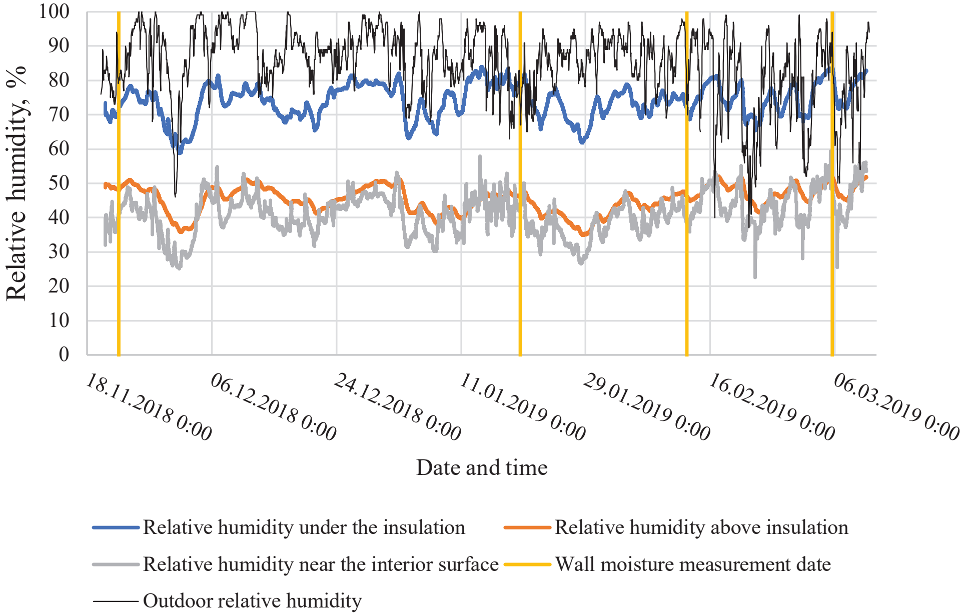

Fig. 2.17. Changes in relative humidity during the monitoring period.

Outdoor weather also affects the conditions between the thermal insulation and the masonry, but no interstitial condensation was observed during the monitoring period. Fluctuations in relative humidity between the masonry and the thermal insulation material (see Fig. 2.17) are related to temperature changes. The highest relative humidity under the insulation material during the monitoring period reaches 84 % and most of the time the relative humidity remains below 80 %. Such moisture conditions do not pose a high risk of mould growth.

Non-invasive humidity measurements were made with the microwave measurement method at a depth of 20 cm and the dielectric method at a depth of 2 cm. The resulting values indicate humidity on a relative scale, from drier to wetter, where 0 is the driest and 250 the wettest value. The lower measurement zone of the wall is up to 0.8 m above the ground, the middle part is from 0.8 m to 1.6 m above the ground, and the upper part is from 1.6 m to 2 m above the ground. In Fig. 2.18, the changes in average values are shown in the upper, middle, and lower parts for the microwave measurements at a depth of 20 cm. An upward trend can be observed in the lower part of the wall during the measurement period. Likewise, the upper section follows an upward trend with a slight decrease from the 1st to the 2nd measurement. The average humidity measurements in January showed a decrease in the average humidity level, but then it starts to follow an upward trend.

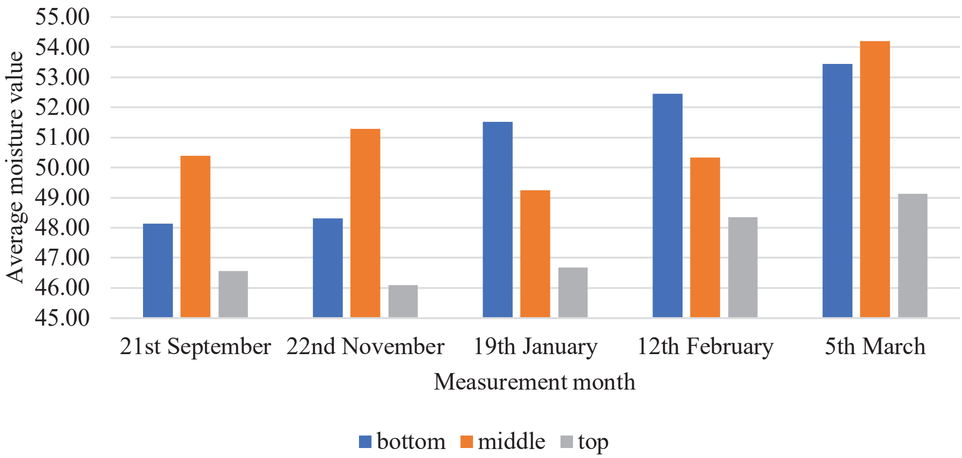

Fig. 2.18. Changes in the average values in the upper, middle, and lower part of the wall for microwave measurements at a depth of 20 cm.

Figure 2.19 shows the changes in average values in the upper, middle, and lower parts for dielectric measurements at a depth of 2 cm.

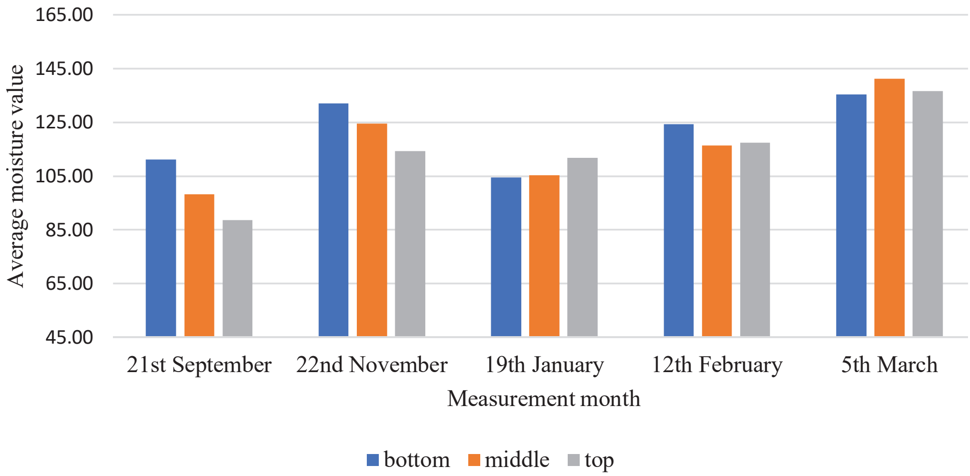

Fig. 2.19. Changes in average values in the upper, middle, and lower parts for dielectric measurements at a depth of 2 cm.

During the research [13], no clear signs of an increase in moisture problems were observed, but it should be noted that the monitoring period was only seven months in the cold period of the year, an increased moisture problem could occur in the warm months of the year. The inhomogeneity of the facade could be the cause of measurement fluctuations, especially for dielectric measurements made close to the surface. For more conclusive results, follow-up should be done for at least one full year. Measurements of wind and rain on the facade and continuous monitoring of humidity at different heights of the masonry should be carried out.

2.4. A block of positive energy balance in a historic urban environment

The blocks with energy efficiency potential are located in the outer perimeter of the Riga historical centre (RVC), while the blocks with higher cultural value are concentrated in the central parts of the RVC, so the decision-making hierarchy set two sub-goals: 1) to find the RVC city block with the highest energy efficiency potential and 2) to find the RVC city block that represents the cultural heritage and urban livability of the highest quality.

The cultural heritage quarter was selected using multi-criteria analysis. Criteria weights are obtained in a pairwise comparison matrix following the analytic hierarchy process methodology. Figure 2.20 reflects the weight of the criteria. Cultural significance and diversity of construction periods have been determined as the most important criteria. From a quality of living perspective, crime protection, good sensory experiences and building renovations are most important.

Within the framework of the study, two distinct quarters were identified, which received the highest rating as a “cultural heritage quarter”. The first block is located at the border of RVC; it includes excellent cultural heritage values – the most notable examples of Art Nouveau in the historical city of Riga. Both cultural heritage and living quality criteria (crime, unpleasant sensory experiences and renovation of buildings) provide the advantage. The second block, which ranks highest in terms of cultural heritage and liveability, is a small urban block in the inner part of the RVC.

Using multi-criteria analysis, the most relevant "energy quarters" were determined. The main goal was to identify the blocks with the greatest potential for transformation into a positive energy balance block. Initially, the blocks were selected based on the following selection criteria: 1) an energy-intensive company is located in the block; 2) the block has at least 10 % residential function; 3) there is an undeveloped plot of land in the city block for highly efficient development. Based on these criteria, 12 blocks were selected for more detailed research and multi-criteria analysis with the TOPSIS method. In Fig. 2.21, the proportions of the evaluation criteria are shown.

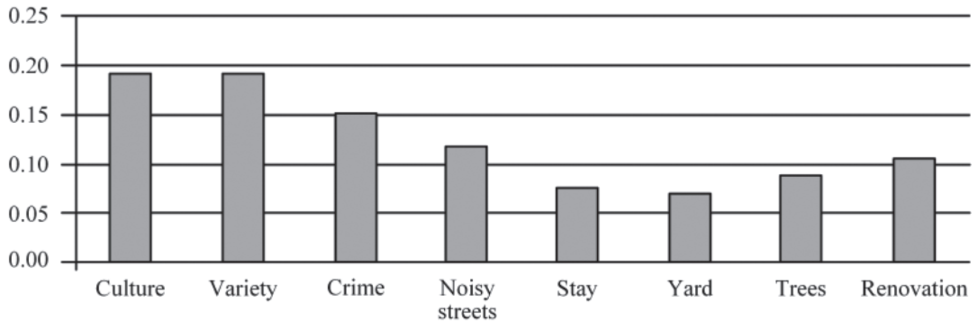

Fig. 2.20. Weight of cultural heritage and quality of life criteria.

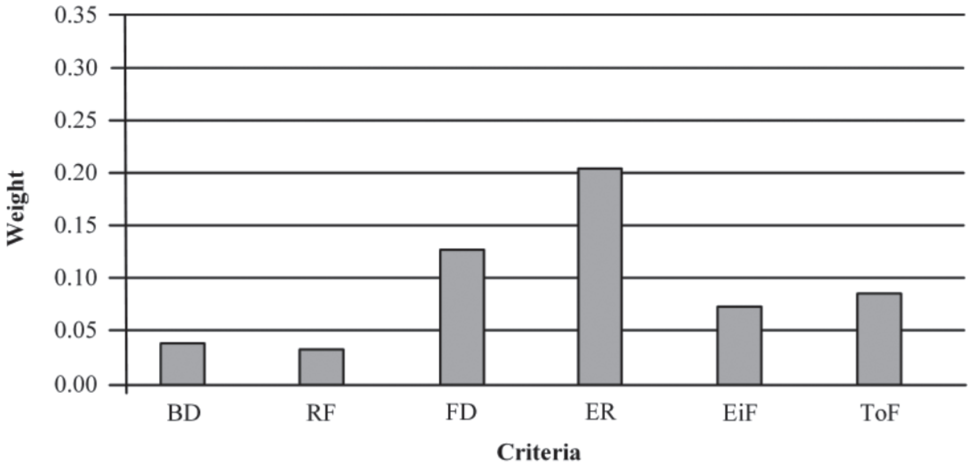

Fig. 2.21. Proportions of energy quarter criteria. (BD – Building density; RF – Residential function; FD – Future development; ER – Possibility of Refurbishment; EiF – Energy intensive functions; ToF – Type of function)

The study shows that high-quality architecture with significant cultural value is concentrated in the central districts of the historical centre of Riga along the main routes, where it once had a representative function – to exhibit technological achievements and conceptually new ideas. Unfortunately, over time, the main routes have lost their role in showcasing new architectural concepts and ideas and have become transport infrastructure. Cars are taking precedence over people, and the most culturally valuable areas are losing their vitality due to traffic. It was found that the blocks with higher habitability are located a little further from the main streets, but still in the central areas of the RVC. These blocks have lower cultural value but higher quality of living characteristics. "Energy blocks" are mostly located on the edges of the RVC. Most of the identified energy-intensive blocks were built after World War II. After the war, public spaces were integrated into the existing urban structure.

The results of the study show that there were only two blocks in both (energy quarter and cultural heritage quarter) lists, but none of them ranked highly in the individual alternative ranking and only one of them was selected for further analysis. Illustrations of the quarter can be seen in Fig. 2.22.

Fig. 2.22. The city quarter selected for the study, which is the most suitable for the transition to a positive energy balance quarter, both from the aspect of energy and cultural-historical value.

When aiming for a carbon-neutral future in 2050, significant attention must be paid to the existing buildings, as they have a high potential for reducing CO_2 emissions. However, it should be taken into consideration that historical urban construction structures are complex: the building density is high, the distance between buildings is smaller than in new blocks, and the historical value to be preserved limits energy efficiency measures. The results of the study on the potential of energy efficiency, the potential of renewable energy resources and the reduction of CO_2 in the selected quarter of the historical centre of Riga. The study's calculations of the potential CO_2 savings of the transition from the traditional historic city block to the positive energy block show a potential of approximately 45 kg/m² of CO_2 savings per year, reducing CO_2 emissions from 50 kg/m² to 5 kg/m² per year and a total of 1627 tons per year. According to the calculated results, the thermal energy demand can be fully covered by locally produced energy (using storage or by feeding the centralized heat supply network), but covering the electricity demand in the case of energy-intensive consumers requires external production. The results show the potential to achieve very low energy demand in this quarter (see Table 2.2).

Table 2.2

Results of the Study on Energy Efficiency Potential, Renewable Energy Potential, and CO_2 Reduction in the Selected Quarter of the Historical centre of Riga

Technology used	**Energy savings**			**Energygeneration**		**CO_2**
	Heating	**Electricity**		**Electricity**	**Thermal energy**	**CO_2 savings**
	MWh	**MWh**	**m²**	**MWh**	**MWh**	**tonnas**
Building energy efficiency related energy savings	2686	2400	–	–	–	970
Waste heat utilization			–	–		
DC Waste heat	–	–	–	–	338	89
Utilized cooling energy demand			–	–	83	22
Energy production						
Usefull rooftop area						
Rooftop area covered with PV	–	–	5965	1014	–	111
Rooftop area covered with PVT	–	–	3895	425	1380	411
Facaders	–	–				
Useful area of South-East facades	–	–	1307	135	–	15
Useful area of South-West facades	–	–	835	89	–	10
				1663	1800	1627
Percentage from total energy demand of selected				69 %	100 %	

CONCLUSIONS

Hypothesis 1

Historic bricks have different hygrothermal properties and affect the hygrothermal processes in internally insulated solid masonry walls.

The hypothesis was confirmed, as the results of testing 40 historical brick samples show that they have different hygrothermal properties. The obtained results show that the distribution of brick samples in clusters is similar to the distribution of brick sample types based on their description, so generalized conclusions cannot be drawn. However, the study observed that the red clay bricks produced between the late 19th and early 20th centuries show a marked difference between the two main clusters, with only two of the samples being in other clusters. Further studies with larger sample sizes are needed to obtain more detailed results on possible clusters. The study of 40 tested brick masonry insulation from the inside with vapour-permeable capillary-active thermal insulation material in a cold climate concluded that all wall samples have very similar temperature trends, while there is a large difference in moisture behaviour. The temperature variation between different types of walls depends on the thermal resistance of the bricks. The moisture content levels differ by a factor of four for different wall types, and the behaviour of the moisture content is very different. The simulation results show that the moisture content in the masonry and the thermal insulation material, as well as the relative humidity between the masonry and the thermal insulation material, is affected by rain and the quality of the glue application. The simulation results show that if the insulation from the inside is done with vapour-permeable capillary-active material in a building located in a cold climate and with a normal indoor humidity load, the relative humidity between the masonry and the thermal insulation does not exceed 96 % and is considered safe. This conclusion applies to both insulation with and without adhesive glue.

Hypothesis 2

Climatic outdoor conditions affect hygrothermal processes in solid masonry walls insulated from the inside.

The hypothesis was partially confirmed because the results of testing different thermal insulation materials show that, depending on the type of thermal insulation system, hygrothermal processes in massive masonry walls insulated from the inside are affected not only by climatic conditions outside, but also by indoor air conditions. It was also concluded that the tested thermal insulation systems have similar thermal behaviour but have different moisture behaviour. Internal insulation has a major impact on the hygrothermal behaviour of the wall, as the relative humidity between the thermal insulation and the masonry wall increases, which, in turn, increases the risk of mould growth, frost damage, and collapse of wooden beams. In structures, there is a heat flow delay between the inner surface and the outer surface of the structure, and its magnitude depends on the boundary conditions – the greater the difference between the indoor and outdoor temperatures, the greater the time lag. The temperature reduction coefficient, which reflects the ratio of the amplitudes of the heat flow waves, differs for different thermal insulation systems and is positively correlated with the vapour diffusion resistance.

The relative humidity under the insulation material is affected by changes in outdoor air temperature and indoor relative humidity. If the outdoor temperature is constant and the indoor relative humidity fluctuates under environmental conditions, the relative humidity under the insulation in vapour-permeable thermal insulation systems with low vapour diffusion resistance behaves like the indoor relative humidity. The delay depends on the values of S_d . The smaller the vapour resistance, the smaller is the time delay for the propagation of the relative humidity wave from the outer surface of the wall to its inner surface, and the greater the ratio of relative humidity wave amplitudes on both wall surfaces. Vapour-tight systems with high vapour diffusion resistance are not affected by the indoor relative humidity, and the relative humidity between the masonry and the thermal insulation depends only on the outdoor air temperature. If the indoor relative humidity is stable and the outdoor temperature fluctuates, in vapour-permeable thermal insulation systems with low vapor diffusion resistance, the relative humidity under the insulation follows the temperature profile. The lower the vapour diffusion, the more closely the relative humidity waves under the insulation follow the temperature profile. For vapour-tight systems, the range of relative humidity values decreases as the vapour diffusion resistance decreases. When indoor relative humidity and outdoor air temperature fluctuate, vapour-permeable systems with low vapour diffusion resistance more closely follow the indoor relative humidity profile.

The results show that the increase in relative humidity under the thermal insulation systems during wind-driven rain is related to the vapour diffusion resistance of the material. The greater the resistance, the greater is the effect of wind-driven rain, reducing the chance of drying of the room side.

Vapour-permeable materials such as cork, blown cork and high-density fibreboard without vapour barriers perform similarly to vapour barrier systems. The relative humidity under insulation is less sensitive to changes in indoor relative humidity and more sensitive to changes in outdoor temperature. Cork is less sensitive to moisture than wood and wood materials.

Numerical experiments in the *Delphin* simulation tool show that the quality of the simulation depends on the input data. In order for the simulation to provide the most accurate input data, all materials, including thermal insulation and grout, should be as close as possible to actual values. Materials should be tested before simulation, and a custom material file should be created for each to make the simulation as close to reality as possible. The study shows that when applying internal insulation to historic masonry in cold climates, it is necessary to carefully evaluate the hygrothermal properties of the combined wall construction of historic masonry and insulating materials. The simulation results may not coincide with the measured data due to the influence of the values of the initial moisture content of the wall as well as the parameter values.

Hypothesis 3

Historical warming masonry and stone walls from the inside with vapour-impermeable thermal insulation in a cold climate is a safe measure for increasing energy efficiency.

The hypothesis was confirmed, as the results of measurements and computer simulations show that warming the exterior walls from the inside with a vapour-impermeable thermal insulation system in a cold climate in the two studied buildings is a safe measure to increase energy efficiency. In both cases, the relative humidity between the outer wall and the thermal insulation system exceeds 80 % for a relatively short period of time in the cold months of the year and does not approach the condensation formation process. The risk of mould formation is low because during the period of increased relative humidity, the temperature is lower than necessary for spore germination and initial mould growth. In both cases, the relative humidity between the wall and the thermal insulation material follows the changes in the outdoor air temperature.

Hypothesis 4

Preservation of historical buildings does not allow achieving a positive energy balance in the historical city blocks.

The hypothesis was confirmed, as the results show that blocks with higher cultural value have lower energy efficiency potential. The proposed multi-criteria analysis criteria to assess cultural heritage, liveability, and energy efficiency potential characterize the specific characteristics of a city block. Also, the results show that in order to achieve a positive energy quarter, very ambitious energy efficiency improvement goals are needed. The study shows that in further analyses of the transition from a traditional historic city block to a positive energy balance block, which must reconcile two conflicting concepts – the preservation of cultural heritage and the concept of "energy efficiency first", each step requires local knowledge: 1) energy efficiency measures must be adapted to the local climate; 2) renewable energy technologies should take advantage of special environmental and climatic conditions; and 3) historical values to be preserved also have a local character.

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