RIGA TECHNICAL UNIVERSITY

Toms Mols

CLIMATE ADAPTIVE BUILDING ENVELOPES

Summary of the Doctoral Thesis

RTU Press
Riga 2021

RIGA TECHNICAL UNIVERSITY

Faculty of Electrical and Environmental Engineering

Institute of Energy Systems and Environment

Toms Mols

Doctoral Student of the Study Programme “Environmental Science”

CLIMATE ADAPTIVE BUILDING ENVELOPES

Summary of the Doctoral Thesis

Scientific Supervisor

Professor Dr. sc. ing.

ANDRA BLUMBERGA

RTU Press

Riga 2021

Mols, T. Climate Adaptive Building Envelopes. Summary of the Doctoral Thesis. Riga: RTU Press, 2021. 32 p.

Published in accordance with the decision of the Promotion Council "P-19" of 9 April 2021, Minutes No. 137.

https://doi.org/10.7250/9789934226427
ISBN 978-9934-22-642-7 (pdf)

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

To be granted the scientific degree of Doctor of Science (Ph. D.), the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council on 29 June 2021 at 14.00 at the Faculty of Electrical and Environmental Engineering of Riga Technical University, 12 k-1 Azenes Street, Room 115.

OFFICIAL REVIEWERS

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

Professor Dr. sc. ing. Ainis Lagzdiņš
Latvia University of Life Sciences and Technologies, Latvia

Professor Habil. Ph. D. Vytautas Martinaitis
Vilnius Gediminas Technical University, Lithuania

DECLARATION OF ACADEMIC INTEGRITY

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

Toms Mols ……………………………. (signature)

Date: ………………………

The Doctoral Thesis has been written in English. It consists of an Introduction; 3 Chapters; Conclusions; 42 figures; 11 tables; 7 appendices; the total number of pages is 84, not including appendices. The Bibliography contains 116 titles.

CONTENTS

INTRODUCTION

While the requirements for energy efficiency in building sector are becoming more demanding, the need to insulate and seal building envelopes has increased. The focus had been deviated from the wellbeing to reaching narrow energy efficiency goals. However, the understanding of indoor climate effect on human wellbeing is growing. Therefore, the need for instruments and solutions that may help find the sweet spot of these challenges has risen.

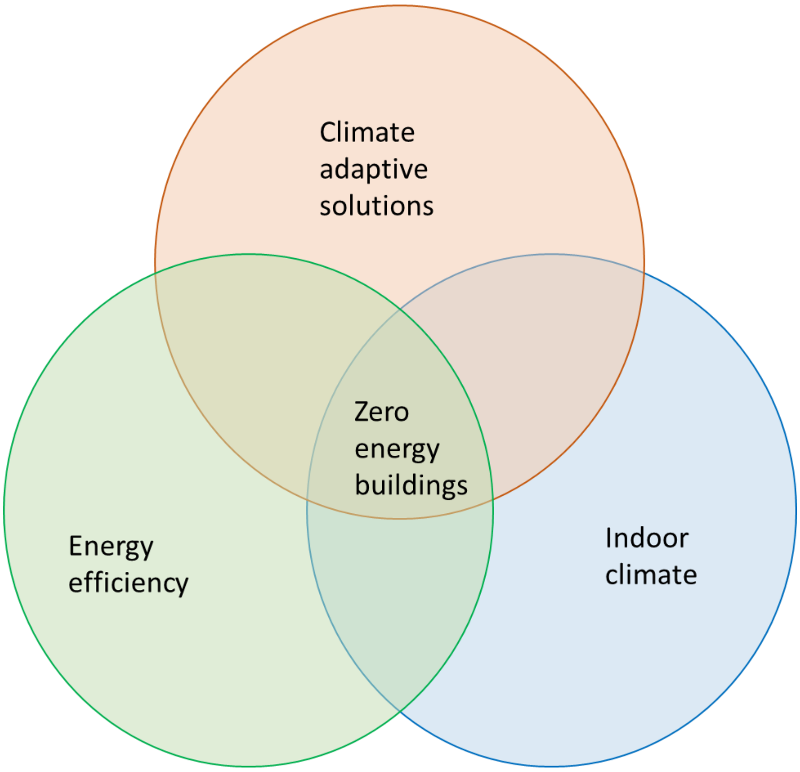


Fig. 1. Energy efficiency and indoor climate requirement overlap with technical capabilities of climate-adaptive solutions.

Climate-adaptive building shell (CABS) is a term in building engineering that describes the group of facades and roofs that interact with the variability in their environment in a dynamic way. CABS are expected to play a significant role in the building sector. Currently the development of the concept has a wide range potential for improvement. This concept has been known in the field of research for more than thirty years but has received special attention only in the last decade. CABS offer the opportunity to improve energy efficiency in buildings, indoor microclimate and maximize the use of 'free' energy that is available, which has a positive effect on the overall energy balance. Given the latest advancements in material development, as well as the development of various sensors and controls, such a shift to adaptive structures should practically not produce any technological barriers, however, as the current situation shows, the innovative and unique use of CABS in buildings is relatively rare. Various CABS descriptions are available in scientific literature, most of which are at the research stage or are developed at the laboratory level. Comparatively fewer are those real examples, developed at the market level, and most of them, for which information is available, are created as individual architectural solutions that have both practical and high aesthetic value (Loonen, 2010; Wang et al., 2016).

The concept of CABS may play a significant role in decreasing energy demand in a building without negatively affecting indoor comfort levels and contemporary lifestyle standards. Additionally, CABS promote use of renewable resources, thus replacing fossil fuel correspondingly decreasing GHG emissions (Wang et al., 2016).

Aim and Objectives

The aim of the Thesis is to develop the methodology for evaluation of climate adaptive building solution application in reaching zero energy buildings.

The main objectives for achieving the goal are:

1) assess the state of indoor microclimate after energy efficiency measure implementation and estimate the affect it has on occupants;
2) identify the possible climate adaptive envelope solutions that may be applied in Latvian climatic conditions and compare them by using the multi-criteria analysis method;
3) evaluate the performance of small-scale solar wall module in various technical variations;
4) develop a system dynamics model for estimation of climate adaptive building envelope solution performance in reaching the zero-energy building level.

Hypothesis

Climate-adaptive building solutions contribute to achieving a zero-energy building level while maintaining good indoor microclimate.

Keywords

Energy efficiency, climate-adaptive building envelopes, phase change materials, passive solar wall, zero energy building, inverse modelling, system dynamics, indoor air quality, multi-criteria analysis, optimization.

Topicality of the Research

It is estimated that energy consumed by building sector needs forms 40 % of the total primary energy use worldwide (Energy Agency, 2013). According to International Energy Agency estimations, if no energy efficiency improvements are carried out in the building sector, energy consumption might increase by 50 % in 2050 (OECD, 2013). As regulatory requirements for environmental impact become more stringent, solutions must be found to reduce buildings energy consumption. Energy costs are rising. Meanwhile microgeneration is becoming more popular among private investors and municipalities.

The wellbeing of people indoors is linked to their performance quality that results in economic impact. If the indoor microclimate is neglected, the negative effect on economic aspects can be far worse than the costs needed for provision of sufficient air exchange and temperature control. Thus these qualities must be taken into account when developing mechanisms that help make building design or exploitation decisions.

Due to constant development of materials and technologies, the technical capabilities have widened and allow the estimation of benefits when incorporating specific climate adaptive building envelope technologies in the design and constructions of domestic and public buildings. To effectively bring corresponding solutions to market, proper analysis and tests must be carried out, and this study is a step towards this goal.

Approbation of the Research Results

1. Mols, T., Blumberga, A. Inverse modelling of climate adaptive building shells. System dynamics approach. (2020) Environmental and Climate Technologies, 24(2), pp. 170–177.
2. Mols, T., Vanaga, R., Blumberga, A. Solar Facade Module for Nearly Zero Energy Building. Extended Test Period (2020) Environmental and Climate Technologies, 24(1), pp. 442–453.
3. Vanaga, R., Blumberga, A., Freimanis, R., Mols, T., Blumberga, D. Solar facade module for nearly zero energy building (2018) Energy, 157, pp. 1025–1034.
4. Mols, T., Dzene, K.P., Vanaga, R., Freimanis, R., Blumberga, A. Experimental study of small-scale passive solar wall module with phase change material and Fresnel lens (2018) Energy Procedia 147, pp. 467–473.
5. Mols, T., Blumberga, A., Karklina, I. Evaluation of climate adaptive building shells: Multi-criteria analysis (2017) Energy Procedia, 128, pp. 292–296.
6. Asere, L., Mols, T., Blumberga, A. Assessment of Indoor Air Quality in Renovated Buildings of Liepāja Municipality (2016) Energy Procedia, 91, pp. 907–915.
7. Asere, L., Mols, T., Blumberga, A. Assessment of Energy Efficiency Measures on Indoor Air Quality and Microclimate in Buildings of Liepaja Municipality (2016) Energy Procedia, 95, pp. 37–42.

Presentation in Scientific Conferences

1. International conference “CONECT 2020; International scientific conference of Environmental and Climate Technologies”. Report “Inverse modelling of climate adaptive building shells. System dynamics approach”, Latvia, Riga, May 13–15, 2020.
2. International conference “CONECT 2018; International scientific conference of Environmental and Climate Technologies”. Report “Experimental study of small-scale passive solar wall module with phase change material and Fresnel lens”, Latvia, Riga, May 16–18, 2018.
3. International conference “CONECT 2017; International scientific conference of Environmental and Climate Technologies”. Report “Evaluation of climate adaptive building shells: Multi-criteria analysis”, Latvia, Riga, May 10–12, 2017.

Structure of the Thesis

The research consists of initial assessment of indoor microclimate in public buildings like schools, daycares, and other municipal buildings. Continuing the study, multi-criteria methodology is applied to evaluate climate-adaptive building envelope technologies that could be successfully applied in Latvian climatic conditions. Specific technology – a small scale solar wall module was tested and improved to monitor the energy performance of such solutions. Finally, with the system dynamics approach an inverse model was developed to estimate the necessary enclosing structure parameters to reach the balance between acceptable indoor microclimate, energy performance and buildings adaptive capabilities to changing conditions.

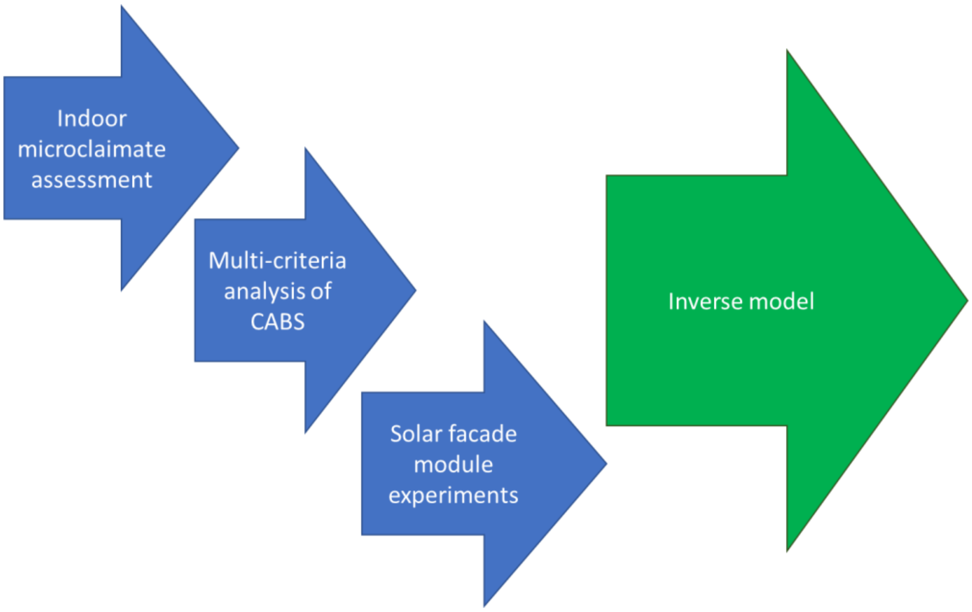


Fig. 2. Methodology used within research.

Scientific Significance

Measurements in actual public buildings have been performed, and the results are linked with possible productivity loss that can be compensated with improved indoor conditions. Therefore, a scientific justification is formed that emphasizes the need for sufficient air exchange in public buildings claiming that the provision would be cost-effective.

Novel small-scale solar wall module experiments have been performed to measure parameters in the module and evaluate the energy performance of various constructive setups. The conclusions allow for further development of the technology and suggest moving to the next stage of technology performance assessment within a large scale wall module in real climatic conditions.

The research has high scientific significance providing a novel methodology for evaluation of solution of climate-adaptive building envelope application. As available building energy performance modelling software did not allow the inverse approach of calculations to full extent, a system dynamics model was created to cover this need. The methodology allows to estimate the necessary enclosing structure parameters to reach desired energy efficiency levels without compromising the indoor climate conditions.

Practical Application

The findings in air quality and CO_2 concentration level measurements in renovated buildings in which ventilation equipment is operating selectively or not operating at all, were linked with person's mental performance and relevant financial impact. This allows for policy makers to create conditions for building managers to allocate adequate funding for provision of indoor air quality. And building inhabitants have significant basis on which to rely when demanding improvements in working conditions.

Building design demands making decisions that will affect the building energy performance for the rest of the exploitation period. The existing approach is to calculate the necessary structure insulation for the worst-case scenario and leaves less room for adaptive mechanisms.

The developed methodology can be applied by architects, designers, real estate developers and others to make construction design decisions on a balanced and factual basis. Therefore, the research has high practical level, as it allows for professionals to apply a more versatile array of solutions thus improving the overall building energy performance.

1. METHODOLOGY

Several assessments of indoor microclimate with prolonged measurements have been developed to determine the state of current situation. The multi-criteria analyses method is used to evaluate the overall application of climate-adaptive building envelope solution in Latvian climatic conditions.

The technologies that were chosen by multi-criteria analyses method have been used for the development of system dynamics model that allows to determine energy efficiency parameters that need to be performed to reach desired indoor air parameters.

1.1. Assessment of Indoor Microclimate

1.1.1. Assessment of Impact of Energy Efficiency Measures on Microclimate in the Buildings of Liepāja Municipality

Assessment of microclimate of five educational institution buildings and three municipality buildings of Liepāja municipality was carried out. All selected buildings have undergone major energy efficiency improvements in recent years, including insulation of building envelope, change of windows and installation of mechanical ventilation systems.

Microclimate measurements were taken during the heating season. Each room was monitored for one week. Two rooms in each of the buildings were selected for monitoring.

Tracer gas method was used to find out air exchange rate. The concentration decay method with sulfur hexafluoride (SF6) was used. The measurements were carried out with LumaSense Technologies INNOVA 1303 (Innova AirTech Instruments A/S, 1997).

The Blower door test was used to determine air infiltration rate in each of the tested rooms. The pressure in the room is increased till 70 Pa. The pressure is gradually decreased by 5–10 Pa by changing the speed of ventilator. Air leakage coefficient (C) and exponent (n) that reflect the leakage parameters in the building are defined by measuring pressure gaps and air volume of ventilation output (Kim, Jo, and Jeong, 2013).

All measurements were recorded every 5 minutes and stored in the device's internal memory. Delta Ohm HD 32.1. is equipped with a battery that helps to operate if there are power disturbances. The results are represented as air quality parameter dependence in time.

1.1.2. Assessment of Microclimate in Renovated Buildings

The interviews with building managers or responsible persons were done in order to get an overview of the buildings. The data about the building types, total area, energy efficiency activities that are collected and the ventilation system that is operated was clarified, and the building plans were studied in these meetings.

People were surveyed in all the rooms to find out their subjective opinion about indoor microclimate in the specific moment. People commented their feelings and opinion and evaluated their comfort level from –3 to +3. The Predicted Mean Vote (PMV) refers to a thermal scale that runs from cold (–3) to hot (+3), originally developed by Fanger. The air parameters in the specific moment were fixed to make further calculations. The calculation of

PMV was made to give an opportunity to compare theoretical comfort level parameters with human subjective feelings. The thermal comfort calculation was made with the Design builder software. It should be noted that these results were obtained considering the thermal conditions in which people reside on the premises and activity level. However, air quality or affecting parameters such as fresh air supply is not taken into account.

R. Kosonen's productivity loss model was used to find out the effect on human performance based on studied buildings microclimate conditions combined with mental work. The ventilation productivity method was chosen to do economical effect and cost benefit analysis because it is applicable for every building and this model has no limited parameters. That gives an opportunity to define economic impact of human productivity changes. The required data for the economic effect and cost benefit analysis are the necessary amount of investments, expenses arising from the operation of the air handling unit and the estimated weighted average of the relative performance improvement percentage.

1.2. Multi-Criteria Analysis

The decision making of multi-criteria analysis was formed in the following stages.

a. Definition of the Problem, Generation of Alternatives and Definition of Criteria

In the wide range of climate adaptive building shell technologies that is found in the scientific literature, magazines and real-life examples a decision of the best fitting technology for Latvian weather climate was made. Subtracting the technologies that are specific for warm climate zones that would just simply not be possible to adapt to Latvian climate a number of reasonable technologies is left – seven different CABS are generated as possible alternatives:

- active window – translucent protection from solar glare and sunshading using micromirrors;
- deployable external insulation – insulative shutters that are moved by phase change wax pistons;
- GlassX crystal PCM – phase change heat storage modules;
- living walls and roofs – reduction of overall temperature of building surface by shading and evaporative cooling;
- liquid façade – water filled chambers with adjustable volume;
- Skytherm solar roof pond – large mass of water stored on the roof forming a source of heating or cooling depending on season;
- solar barrel wall – heat storage barrels with lids to control heat gains and losses (Moloney, 2011).

b. Weighting of Criteria

With the help of experts of energy efficiency sector, the previously mentioned criteria are weighted in order to understand the impact of each criteria to the total result.

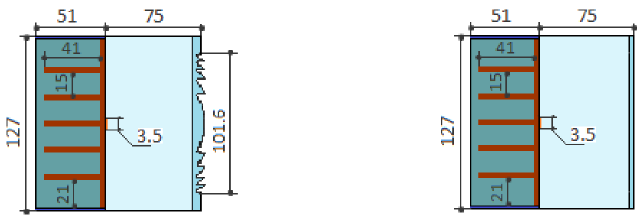
c. Matrix of Criteria and Choosing the Appropriate Method

When weighting of criteria is completed, it is possible to arrange the equation in a matrix with criteria, weight and alternatives. In order to have a transparent and simple method for choosing the appropriate climate adaptive building shell technology, Simple Additive Weighting (SAW) is used. The method allows to see, interpret and judge the effect of criteria and subcriteria at every stage (Kaliszewski and Podkopaev, 2016).

1.3. Experimental Study of Solar Wall Module

1.3.1. Experiment Setup with Small-Scale Passive Solar Wall Module with Phase Change Material and Fresnel Lens

Test module gains heat by solar radiation (Tawfik, Tonnellier, and Sansom, 2018); it is captured and concentrated using Fresnel lens and concentrated on heat transfer enhancer – copper plate with fins that heats PCM and transfers heat to room. To assess impact of Fresnel lens on energy balance of the test module, PMMA acrylic glass is used instead (Fig. 1.1). PCM is paraffin RT21 HC (650 mL) with specific heat capacity 2 kJ/(kg K), melting temperature 20–23 °C, solidification temperature 21–19 °C, latent heat of fusion 190 kJ/kg, thermal conductivity 0.2 W/(m K) and density solid/liquid 0.88/0.77 kg/m^3 (GmbH Rubitherm Technologies, n. d.). Heat transfer enhancer is a copper plate with copper fins embedded in PCM. Fresnel lens is made from PMMA (127 mm × 127 mm) with focal point 71 mm (Edmund Optics Inc., n. d.). The air gap between the copper plate and Fresnel lens / PMMA acrylic glass is 74 mm.



a) b)

Fig. 1.1. Cross section of the test module with a) Fresnel lens and b) PMMA acrylic glass.

Two test boxes with (1) a reference wall and (2) a wall with test module are placed in the climate chamber. The size of each test box is 557 mm × 557 mm × 600 mm. The outer shell is made from 15 mm thick plywood. The inner part of walls are made from mineral wool (200 mm to 300 mm). The size of inner room is 140 mm × 140 mm × 127 mm.

The outer part of the front side of both test boxes is covered with reflective material. Two halogen lamps (500 W each) are used as solar simulator (Fig. 1.2). The distance from solar simulator and test boxes is 1520 mm. After solar simulator is switched off, room temperature is cooled down and kept at +12 °C ± 1 °C.

Fig. 1.2. Experimental setup with solar simulator and two test boxes (the reference wall on the right and the wall with test module on the left).

1.3.2. Experimental Setup. Solar Facade Module for Nearly Zero Energy Building in External Conditions

In the experimental study, two test boxes located side by side each other with and without facade module were monitored during September 2017. Both test boxes were placed on the roof of the building and exposed to identical boundary conditions. Test boxes were faced South and were shaded from all other sides (Fig. 1.3). Both boxes were instrumented to monitor the outdoor climate (solar energy, wind, relative humidity), indoor temperature, heat transmission through the building envelope, and temperatures in the phase change material. Data gathered during the monitoring period were analyzed and used to calibrate a simulation model which was used to perform annual and seasonal energy balance assessment.

Fig. 1.3. Experimental test box with the facade module (left) and reference box without facade module (right).

Experimental Setup

Both test boxes are built from plywood, filled with 20 cm mineral wool and have a room (22.7 cm × 12.7 cm × 12.7 cm) in the centre of the box. The experimental solar facade module has been replaced with mineral wool in the reference test box. The experimental solar facade module is built from commercial materials and consists of different parts. The focal point of Fresnel lens (Figs. 1.4 and 1.5) is installed on the outer shell of the module. The focal length is 7.1 cm, lens effective diameter 101.6 mm, a surface of focal spot 9.6 mm^2, and transmittance is 0.92. It is made of PMMA plate (Edmund Optics Inc., n. d.). A copper plate (113–119 mm) with copper rods is used to enhance thermal transfer within phase change material. 25 copper rods with 5 mm diameter are welded to the plate within the 15 mm distance. The cone for aerogel filling is built from the self-hardening modelling clay DAS. Aerogel granules LA1000, produced by Cabot, with low thermal conductivity and high solar energy transmittance are used between the cone and the copper plate to reduce thermal losses from the copper plate. Paraffin RT21 HC produced by Rubitherm Technologies GmbH is used as the phase change material which is filled in the container with inside dimension of 119 mm width, 110 mm in height and 47.5 mm in depth. One wall of the container is the copper plate with enhancers, while the other five walls are made of 4 mm thick glass.

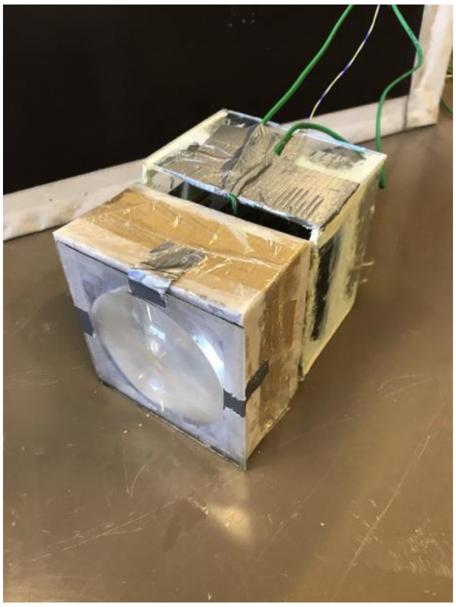


Fig. 1.4. Fresnel lens incorporated in the facade module.

Fig. 1.5. The facade module built in the experimental test box. Total calculated *U*-value of the solar facade module is 0.22 W/(m^2K) and of the reference wall 0.28 W/(m^2K).

The longitude of the experimental site is 2 404 048.700 E and latitude is 5 657 003.000 N.

Instrumentation

The instrumentation scheme of monitoring equipment includes monitoring of indoor temperature, outdoor temperature, solar radiation, temperature in PCM in three layers, and heat flux on the external surface of copper plate and the indoor side of PCM container. Solar flux data are measured with a pyranometer with accuracy of ±10 W/m^2 or 5 % from the reading. Outdoor and indoor temperatures are measured with K type thermocouples with accuracy of ±1.1 °C or ±4% of reading from 0 °C to 1250 °C, and ±2.2 °C or ±2 % of readings from 200 °C to 0 °C. Heat flux is measured with Sequoia heat flux plates. All measurement data are saved in a Campbell Scientific CR1000 data logger. A 1 min time step for all measurements is taken.

1.3.3. Experimental Setup. Extended Test Period

This study of PCM module is a succession of series of passive solar wall research (Mols et al., 2018; Sirmelis et al., 2019; Vanaga et al., 2018). After the review of previously received results the following was decided:

- to add additional test setups of the module using heat exchange enhancers – fine copper wires submerged in PCM;
- to test the module in specific outdoor temperature conditions for a longer – two-day period;
- to adjust testing conditions increasing the power of solar radiation simulator to reach higher melting rate in the PCM.

Eight small scale passive solar wall modules were constructed and tested in a laboratory in a precisely controlled environment. Each module encompasses two main elements – PCM container (127 mm × 127 mm × 60 mm) supplemented with heat transfer enhancers and heat transfer unit (127 mm × 127 mm × 71 mm). Table 1.1 lists the constructive differences among all 8 tested setups.

Table 1.1

Constructive Differences in Test Setups

Setup	Constructive components
Setup 1	Fresnel lens, cone and aerogel
Setup 2	PMMA glass and aerogel
Setup 3	Fresnel lens and aerogel
Setup 3.1	Fresnel lens, aerogel, without fine metal enhancer
Setup 4.	Fresnel lens and air
Setup 4.1	Fresnel lens, air and fine metal enhancer
Setup 5	PMMA glass and air
Setup 6	PMMA glass, cone and aerogel

Additionally, two solar modules are made: PCM container with heat transfer enhancer – fine copper wires (Fig. 1.6), combined with Fresnel lens and aerogel and PCM container without heat transfer enhancers combined with PMMA acrylic glass and no insulation material.

Fig. 1.6. PCM container with fine copper wires as a heat transfer enhancer element.

The phase change material Paraffin RT21 HC (Rubitherm) with characteristics listed in Table 1.2 is used for this experiment.

Table 1.2

Main Characteristics of Paraffin RT21 HC (GmbH Rubitherm Technologies, n. d.)

Melting temperature	20–23 °C
Solidification temperature	21–19 °C
Solid at	15 °C
Liquid at	25 °C
Heat conductivity	0.2 W/(m K)
Heat storage capacity	190 kJ/kg

A special halogen lamp GE SUPER CP60 EXC VNS 230 V | 1000 W G16d 3200 K | General Electric combined with dimmer UNI BAR Elation professional was used to simulate solar radiation that acts on wall module. The wall modules were exposed to solar radiation of 1000 W/m^2 during the heating phase.

The distance between the solar radiation simulation lamp and test box was kept repeatedly at 2329 mm (Fig. 1.7). The experiment lasted 48 hours with solar radiation available for 7 hours 39 minutes (outdoor temperature +15 °C) from the beginning of the testing period. For the rest of the period, 40 hours 21 minute, the temperature in the refrigeration chamber is maintained at +10 °C.

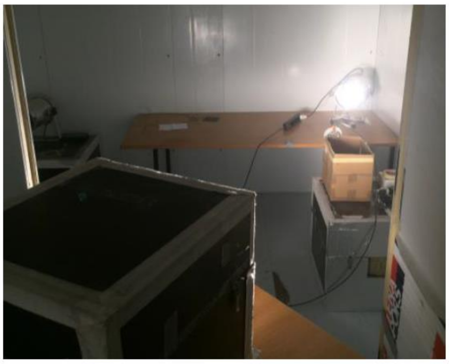
 

Fig. 1.7. Experimental setup.

Monitoring Equipment

Parameters during the experiment were registered via Multipurpose data logger CR1000 | Campbell Scientific combined with multiplexer AM16/32 | Campbell Scientific. Data is logged once every minute. Solar radiation is measured by pyranometer CMP3 | Kipp & Zonen. Type K thermocouples are used to measure temperature.

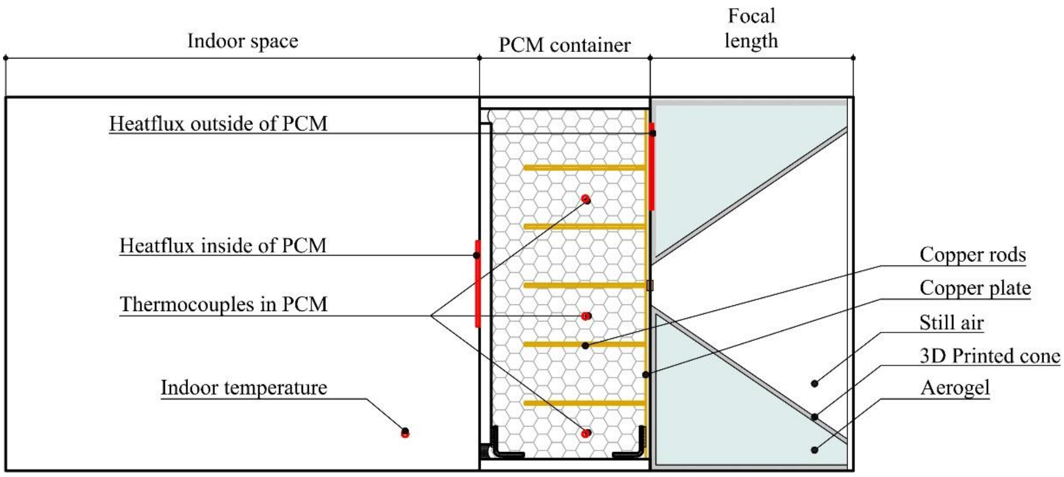


Fig. 1.8. Monitoring equipment scheme.

By analogy with the preceding experimental study there were 5 thermocouples used to collect the temperature data during the experiments (Fig. 1.8). Three thermocouples were in the PCM container close to the back wall to monitor heating and heat distribution process in different layers – lower, middle and upper layer. The fourth thermocouple measured the indoor space temperature. The fifth thermocouple was placed outside the box at the wall of refrigeration camera to log the ‘ambient’ temperature.

Two Sequoia SHF meters were placed on the outside and inside walls of the PCM container to collect heat flow data. Heat flow meters provide information on the heat transfer process dynamics in the solar wall module.

1.4. Inverse Modeling

System Modelling Software: Requirements and Restrictions

In this research climate adaptive building envelopes are considered to not only improve energy performance of the building but improve or maintain the needed microclimate for building occupants to perform their best.

A large part of building modelling tools has evolved gradually, providing the user with ever new opportunities. The modelling and simulation of adaptive buildings should show how the structure of the building or the specific parameters of the building change. At the time when building modelling software was designed, it was not designed for modelling of adaptive building designs, therefore, most of the available modelling tools lack a wide range of possibilities for determining the CABS performance, since the construction parameters in these tools are defined as constants and remain constant throughout the simulation, therefore, applied and sought simplified simulation approaches were used. A few of the most commonly used modelling software tools are (ESP-r, n.d.; Laicane et al., 2015; Loonen et al., 2010; 2017) Energy plus, TRNSYS, and ESP-r.

Requirements and Restrictions for Existing Building Modelling Tools

From all of the modelling tools discussed, EnergyPlus has been powered by the most comprehensive CABS modelling and simulation capabilities since its inception, gradually evolving and developing to meet today's needs. It is important to mention that this is a free, open source software tool that makes it more attractive to the user than for instance TRNSYS software tool. There is wide potential for development and improvement with regard to the possibilities of modelling software tools, which in the future will provide wider possibilities for CABS modelling and simulation (Harish and Kumar, 2016; Loonen et al., 2014).

The stock describes the accumulation of values and the decrease in value through incoming and outgoing flows. The parameters are used to merge and/or reformulate the information. The constants define constant values for all simulations. Information links link resources, ancillaries and constants to each other and show how individual elements of the model are interconnected (Powersim Studio 8 Academic (8.10.4916.6), n. d.).

Inverse Modelling

Building modelling approaches can be divided into two categories: 1) classical (direct) modelling and 2) reverse (inverse) or data-driven modelling. Direct modelling as input data takes physical measurements of the building, which may include the location of the building, local weather, geometry, construction materials, operating schedule, type of heating ventilation and air conditioning system, etc. Direct modelling is usually used in the design phase of buildings. The inverted model uses data from the building's energy consumption data, expressed as one or more variables and an empirical set of parameters, as input data. The input data is used to find the parameters that provide the best fit for the selected model and data set (Favoino, Overend, and Jin, 2015; Kramer, van Schijndel, and Schellen, 2013).

The energy balance in the study by Bart de Boer et al. is expressed as an equation of three variables: *U*-value, air exchange rate and solar heat gain coefficient, therefore one unique solution cannot be found. When modelling the minimum hourly energy balance value [energy balance is generally expressed as the difference between heat gain (from the sun and humans) and heat loss (through the facade and ventilation)], maximizing the use of solar energy is prioritized by reducing heat loss through the facade and ventilation – when such a solution generates excess heat, the benefits of solar heat are first reduced, and only then the heat transfer and ventilation are increased (Andr, Evgrafov, and Patriksson, 2005; Boer et al., 2011).

Most of the available modelling tools lack extensive capabilities to measure the CABS's performance, so researchers are always looking for ways to make better use of existing tools or develop new tools that are not widely available.

Inverse modelling is closely related to optimization. When dealing with climate adaptive building shells, it is essential to choose the right values among many systems.

Optimization Software

Even though many different optimization tools are available that provide a variety of features, the desire to create new optimization tools still exists. The need for a universal optimization tool, which is free, can be integrated with other modelling tools and eliminates the gaps in existing optimization tools, serves as the main motivation factor for Academy of Finland funded optimization tool Mobo (Multi-Objective Building Optimization) creation (Palonen, Hamdy, and Hasan, 2013).

When optimizing the building, among the very large number of possible combinations, it is possible to find the optimal values of the variables that simultaneously fit within the specified boundary functions and satisfy the target functions. Examples of optimization targets in buildings can include environmental aspects (energy consumption, emission reductions, energy efficiency), costs, comfort level, etc. Optimal solutions can be sought for each case individually and simultaneously – by multi-objective optimization (Favoino and Overend, 2015; Kasinalis et al., 2014; Palonen et al., 2013; Stephan, Bastide, and Wurtz, 2011).

System Dynamics Model for Climate-Adaptive Building Envelopes

The model is created for a general case without dividing a particular climate-adaptive building envelope. The function, which is based on all active window technologies, is the ability to change the solar heat gain coefficient (*g* value). The model determines that the solar heat gain coefficient can vary within certain limits, but the way this change occurs (external, internal blinds, reflective light elements, etc.) is not reflected in the model.

The energy consumption of a building can be calculated by determining the heat output and heat loss of the building, which forms the energy balance of the building. Such a process is the basis for any energy audit of the building. As a basis for the active window model built in the Powersim Studio environment, the renovation of the building described in the manual on sustainable building design and engineering is used; in this case, all the necessary parameters characterizing the building are made available, which facilitates the creation of the model (Mumovic and Santamouris, 2009).

To determine the most suitable solar heat gain coefficient, model optimization in Powersim Studio environment was made. For each hour a corresponding heat gain coefficient value was calculated so that the energy balance would be equal to zero. This was defined as a constraint. In the model energy balance had been defined as objective function, whereas solar heat gain coefficient is variable ranging from 0.06 to 0.85.

2. RESULTS

2.1. Microclimate Assessment Results

Tracer gas tests show that air exchange rate from 0.19 till 0.40 has been fixed in educational institutions and in other institutions – from 0.33 to 0.57. It means that the air exchange rate is too low because of energy efficiency activities in these rooms. The air movement results indicate that high air exchange rates in long term have not been found. That describes the current ventilation system that operates irregularly or does not work at all. Air exchange rates in Liepāja municipality buildings are visualized in Fig. 2.1.

Fig. 2.1. Air exchange rates in Liepāja municipality buildings.

Taking into account the level of activity, the air temperature should be from 19 °C to 25 °C according to the national cabinet regulation No. 359 (Ministru Kabinets, 2009) on occupational health and safety requirements in the workplace. The microclimate measurements did not meet requirements most of the days while the research was done.

The temperature measurements are either insufficient or too high in all rooms. In one of the studied areas the air temperature outside working hours is below the required minimum and only in the first hours of work it reaches the lowest allowable value – 19 °C. By contrast, the temperature in another room is very high and short-term room ventilation by opening windows cannot provide even a temporary effect. After venting, the air temperature is reduced and then it rapidly recovers the initial value. The windows were open to ventilate rooms only once or twice a day based on the measurement results. This points to an incorrect operation of the building, because energy efficiency measures reduced the natural air exchange layer and it could not be compensated manually.

2.1.1. Interview Results

In the interviews the manager of the buildings showed that the ventilation system was operated mainly manually. That is a subjective evaluation, and the system is not working with

CO_2 sensors or automation that increase maintenance costs. That is happening mostly because of high exploitation costs and building managers try to avoid that in winter period. All buildings have changed windows, part of them have insulated building envelope and roofs and installed mechanical ventilation systems.

The calculated PMV values are mostly within –0.5 and +0.5; however, almost all surveys indicated people subjective assessment from +0.67 to +1.86 that indicates indoor environment as warm and unsatisfactory.

The numerical value of performance loss for room C2 was not calculated because PMV for this room was too high – 2.86. As it is illustrated in Fig. 2.2 rooms B1, D1 and E1 are the most suitable for working with small physical effort.

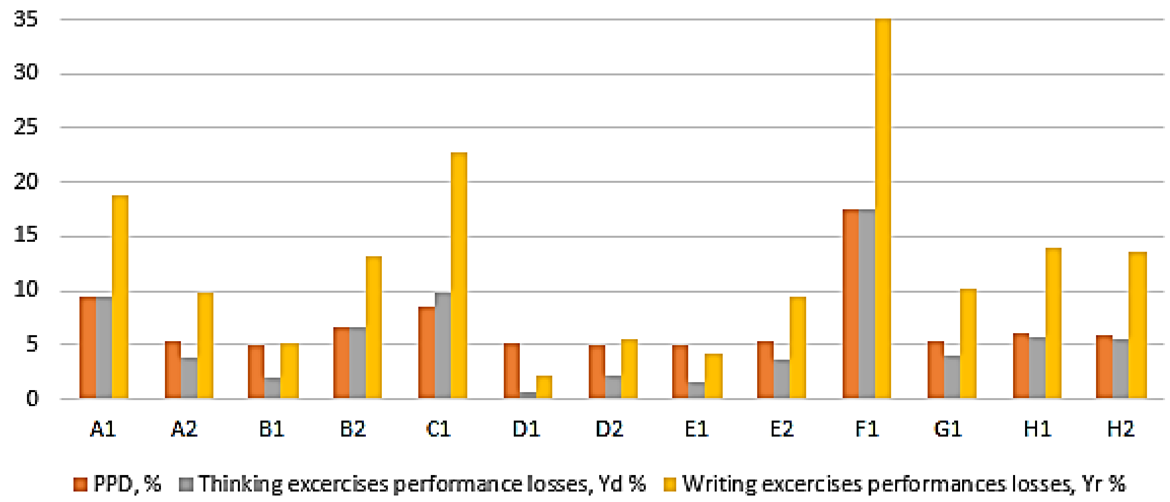


Fig. 2.2. Performance losses based on PPD.

2.2. Multi Criteria Analysis Results of Possible Climate-Adaptive Building Envelope Technologies Applicable in Latvia

The results of weighting indicated that the heaviest of impacts is brought on by the total cost of ownership and the complexity of CABS construction. In the same time the ability for the occupant to interact with adaptive elements of the building are valued much less. Same as esthetic value will also have a small impact in the decision making.

Ranging of Alternatives

To choose the best fitting climate-adaptive building envelope technology to be inspected for the climate of Latvia many factors were considered. Each of the technologies or alternatives were valued by all of the defined criteria and given an appropriate score. Figure 2.3 displays the results of ranging the alternatives. The highest score belongs to a technology where phase change materials were used. The results show that it would be reasonable to consider also the solar barrel wall technology for Latvian climate (Kancane, Vanaga, and Blumberga, 2016).

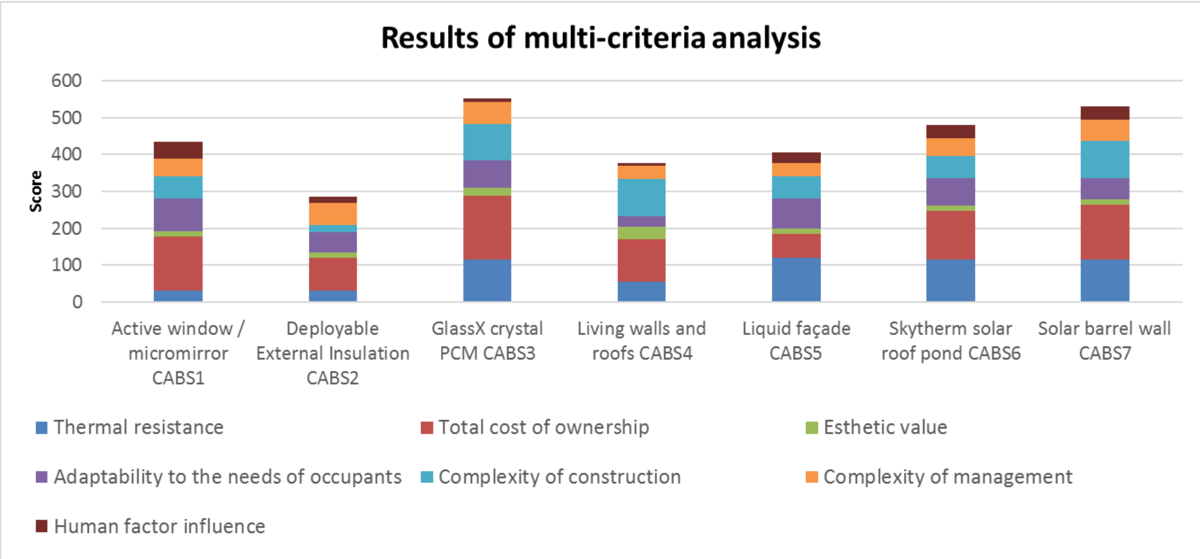


Fig. 2.3. Results of multi-criteria analysis.

2.3. Experiment Results

2.3.1. Experiment Results with a Small Scale Passive Solar Wall Module with Phase Change Material and Fresnel Lens

Solar radiation is kept constant at 560 W/m^2 for 6 hours. Solar simulator is switched on in the first minute and switched off in the 360th minute. Changes in the indoor temperature in climate chamber in the front and the back of the test boxes are observed.

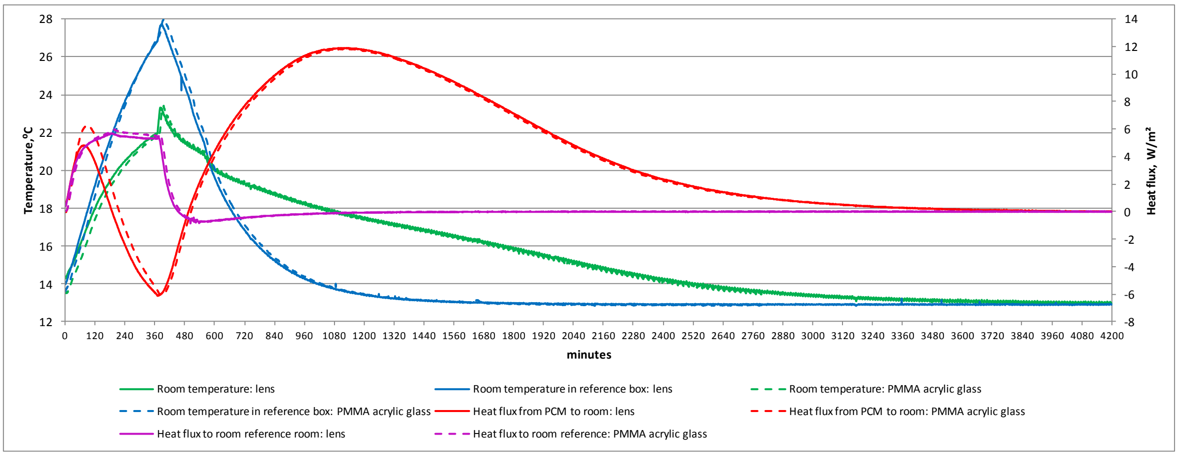


Fig. 2.4. Temperatures and heat fluxes in the reference wall and in the test module with lens or PMMA acrylic glass.

After solar simulator is switched on, the room temperature starts to increase in both boxes and reaches its maximum value when the solar simulator is switched off. In the 360th minute sudden temperature spikes are observed in both boxes. One of the causes can be air leakage into boxes created by the climate chamber cooling fan which is switched on immediately after the solar simulator is switched off. Temperature in the test box is decreasing at much higher rate and reaches equilibrium in the 1700th minute compared to the test module box which cools down slowly until the equilibrium temperature in the 3520th minute. Temperature patterns are similar for test modules with lens and PMMA acrylic glass.

2.3.2. Heat Flux and PCM Performance in Small Scale Solar Wall Module

Heat fluxes and temperatures were measured within and on both sides of the module for one day (September 25, 2017). It was done in the midnight when the solidification of PCM generates latent heat which causes heat flux to both indoor and outdoor. The flow from PCM to outdoor is higher than to indoor due to higher temperature difference. When the sun starts to rise at 7:05, heat flow from outdoor to PCM changes direction and becomes positive at 9:05. Meanwhile, heat flux to room starts to fall and then increases again at 13:30. When the solar radiation decreases at 13:22, so does the heat flux to PCM until it becomes negative at 16:55, i.e. heat losses from the module to outdoor. During the night, solidification of the PCM starts when the latent heat is released at about 23:40 and both heat flux to indoor and outdoor increases. However, indoor temperature falls because the heat flow to outdoor dominates over heat flow to room.

2.3.2.1. Experiment Results with Small Scale Passive Solar Wall Module with Phase Change Material – Extended Test Period

Process of Experiment

One testing cycle of 48 h is monitored during which the PCM is charging and discharging. The duration of the charging phase is 7 h 39 minutes, constant solar simulation 1000 W/m^2 and ambient temperature of 15 °C. The duration of discharging phase is 41 h 21 minutes at an ambient temperature of 10 °C.

Heating and Cooling Temperatures of PCM

Like in the previously performed research (Sirmelis et al., 2019) the heating of PCM occurs gradually from the upper to lower layers of PCM volume. To analyze the solar wall module performance, average values of temperature are calculated from collected measurements (Fig. 2.5).

Average PCM temperature is beginning to rise rapidly at 3 hours 33 minutes in modules with Setups 3.1, 4, 4.1. and 5. Whereas Setups 1, 2, 3 and 3.1. show accelerated temperature increase only at 5 hours and 30 minutes when average PCM temperature has reached 23.6 °C and above. Lastly, Setup 6 does not even reach the PCM melting temperature. Periods with a steep increase of temperature indicate changing to sensible heat.

The solar radiation simulator is turned off after 7 hours 39 minutes of functioning. All of modules excluding Setup 6 show continuation of temperature increase after the solar radiation simulation has stopped. This momentum is explained by PCM layers or fractions that have not melted completely. Whereas, if the whole PCM volume has melted, the cooling commences at the moment solar radiation is interrupted.

As the testing and monitoring period of this experiment was longer than previous research – 48 hours instead of 24 hours, it can be observed that after one day the average PCM temperature, excluding Setup 6, is in the range from 19.95 to 21.42 °C. In this moment the leader is Setup 3.1. with other setups following closely. Continuing the monitoring, the difference between leader and others increases. At the end of the two-day period, the leading Setup 3.1 is at 14.23 °C and Setup 4.1 follows with 13.15°C making a 1.08 °C difference.

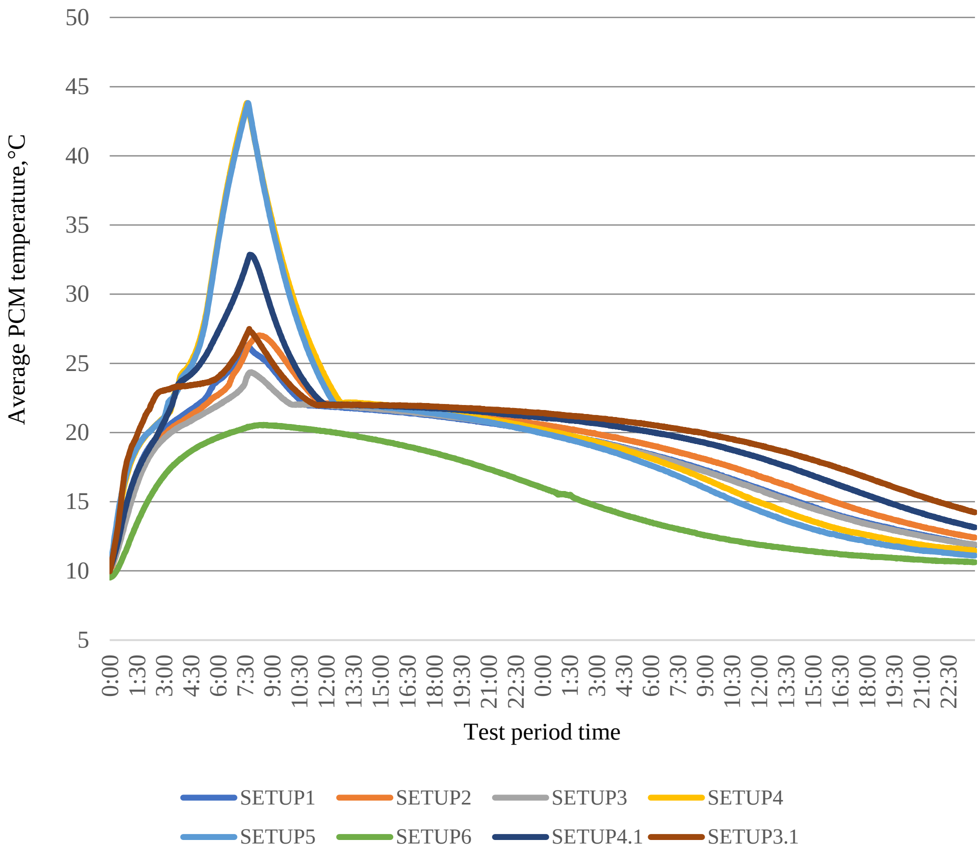


Fig. 2.5. Average PCM temperature in various setups, °C.

Room Temperature

The indoor space temperatures of modules were monitored. By analogy with preceding studies, the indoor temperature continues to rise and reaches its peak values after the solar radiation simulation is stopped. This observation indicates that thermal energy from PCM volume continues to provide heat for indoor space while the external conditions have changed. The highest temperature can be reached via Setup 4 – the same as with average PCM temperature.

Reviewing monitoring results after first 24 hours, the leader of indoor temperature is Setup 4 at 18.17 °C with other Setups following closely. However, after a complete two-day period, the leaders change – Setup 3.1 is at 12.83 °C and other Setups follow leaving Setup 6 only at 10.53 °C that is 0.53 °C above external temperature of testing environment.

2.4. Inverse Model Results

After the model simulation, the result obtained is shown in Fig. 2.6 with a green line. When comparing the energy consumption data with the outdoor air temperature values, it is seen that the simulation data obtained are in line with the expected scenario – the colder the outdoor air temperature, the higher the energy consumption. A purple line shows the result obtained after optimization.

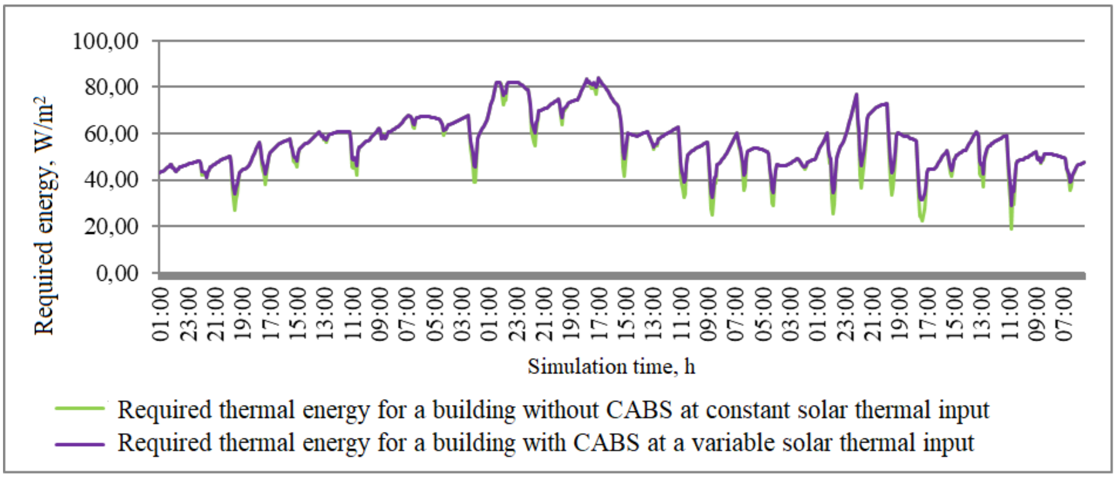


Fig. 2.6. Required energy with and without CABS in January month.

According to Fig. 2.6, the use of CABS, which adapts to the solar radiation level during the winter, would yield minimal benefits due to relatively low solar radiation values. Proposals for a percentage gain result in a potential reduction in thermal energy of just over 1 %.

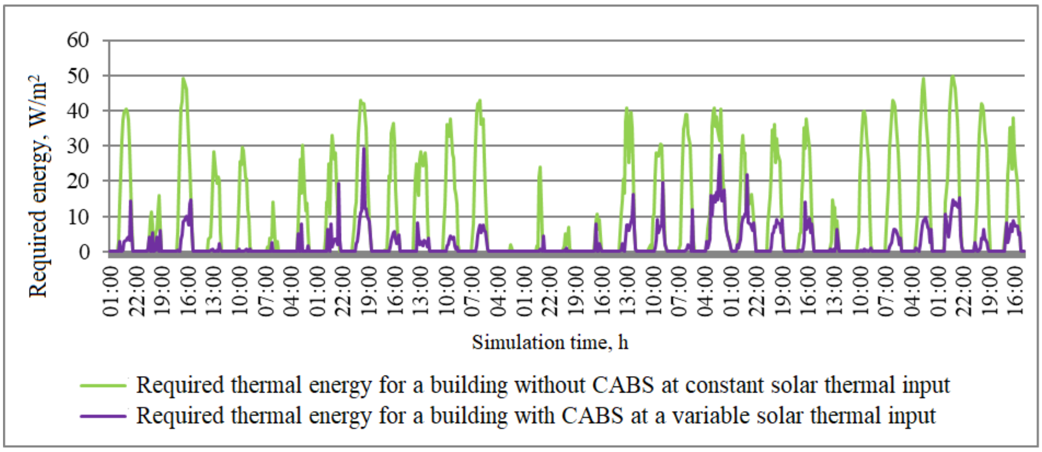


Fig. 2.7. Required energy with and without CABS in July.

Comparing the results obtained between January and July, it is clear that the technology in question has the greatest benefits in terms of cooling capacity reduction (Fig. 2.7). Similar findings are also mentioned in the publications by F. Favoino et al. and A. Taal and L. Itard. During the summer, simulations show a minimal amount of solar gain, but in winter, on the contrary, the adaptive design tries to maximize the benefits of solar heat but the potential for energy savings is minimal. In the winter months, when the solar radiation is low, buildings in the cold climate zone need to look for another more suitable CABS solution (Favoino and Overend, 2015; Kramer et al., 2013).

CONCLUSIONS

In the following paragraphs the main conclusions of the research are listed, as well as suggestions and recommendations for further research.

1. The PMV values in 12 rooms out of 14 inspected within research vary from –0.5 to 0.5, which should mean that persons are feeling comfortable; however, the surveys showed subjective assessment from +0.67 to +1.86, which indicates indoor environment as warm and unsatisfactory. The carbon dioxide and air velocity measurements were done in the same time as surveys. In most buildings the CO_2 measurements are over 1000 ppm and air velocity is too low. It is possible that bad microclimate affected human subjective assessment about thermal comfort. The field study in Liepāja municipality shows that buildings are airtight and thermal comfort indoors is not adequate (Asere, Mols, and Blumberga, 2016).
2. The multi-criteria analysis results indicate phase change material technology for the application in climate adaptive building shells in Latvian climate conditions as the most appropriate. It is suggested that solar barrel wall technology must also be considered suitable for further research.
3. The results of tests with a small-scale solar wall module with PCM reveal that the test modules with Fresnel lens and PMMA acrylic glass show almost the same results, thus use of Fresnel lens as solar concentrator does not give any thermal improvements in this technical solution.
4. The study showed that the dynamics of heat flows and accumulation processes in the developed solar facade module are very complex due to highly changing outdoor and indoor conditions. Experimental results show that the dynamic behavior of the room temperature and heat flux in the reference box made from mineral wool differs from the same parameters measured in the solar facade module. The heat flux in the reference box coincides with the delayed solar radiation and at its maximum peak is around four times less than in the solar facade module. The room temperature in the reference box differs from the module between 0.5 °C during the day and 5 °C during the night due to the impact of the thermal energy accumulation in the PCM. The time lag between solar radiation and the PCM temperature is 3.5 h while between the PCM temperature and indoor temperature it is 45 min. The indoor temperature peak in the reference box is delayed from the solar radiation peak for 4 h.
5. The continuation of the study and continued tests of a passive solar wall module for an extended period of time presented results of the impact of phase change material embedded in the thermal envelope on indoor temperature in the heating season. The experimental study of passive solar wall modules containing PCM provided the following findings:
   a) the 48-hour testing cycle discovered that after a longer period of observation, the technological leaders and rankings change compared to the results from a 24-hour testing cycle;

b) the study shows solar module behavior in the first 24 hours similar to the results previously tested, thus confirming the observations of previous studies;
c) module Setups that allow for reaching stable heat flow fast and respectively melt PCM volume more effectively, create a problem of not managing to harvest more of the available solar radiation. Optimization with PCM material and volume should be carried out in order to find a solution. The ideal Setup of solar module would rapidly harvest solar energy and then enter self-insulated condition that allows for maximum of thermal energy to be emitted indoors;
d) significant differences of peak indoor temperatures were detected. Modules that can harvest more solar radiation in the charging phase are exposed to higher heat losses at the discharge phase to the external environment;
e) the highest indoor temperature was reached with Setups 4 and 5. However, this heat was lost ineffectively dissipating to external environment. The highest indoor temperature after a 48-hour period was detected with Setup 3.1 via Fresnel lens, aerogel and without fine metal enhancer. These observations suggest that the application of metal enhancers should be carried out and continuous tests with and without enhancers should be concluded;
f) the indoor space volume within this research and testing is relatively small and greater volumes might affect the performance of PCM modules. The interaction between changing energy demands and heat emitted from the PCM module should be explored in further research.

6. The described tests and results indicate the performance capabilities and points of improvement for solar module designs and may be of assistance in further research and development of adaptive building envelope.
7. It is suggested for further passive solar wall module research to consider:
   a) possibilities to optimize passive solar wall module construction taking advantage of the fact that upper layers of PCM volume are warming up faster than lower layers;
   b) continuing optimization of metal fraction in PCM;
   c) scaling the testing on a larger scale with solar wall module application in outdoor environment with real weather conditions.
8. Modelling tools for buildings play an important role in the construction design phase of the initial building to look for specific questions and consider different potential scenarios for heating, cooling or renovation approaches when assessing the energy balance of the building and the cost of energy before the project is implemented. The most well-known tools for modelling building performance are subject to a number of constraints that preclude the precise estimation of climate-adaptive building envelope performance and benefits, therefore there is a demand for new and effective software tools, as well as creative and innovative approaches are being sought on how to make the most efficient use of available software tools to get as accurate as possible building models that include CABS. The performance of several climate-adaptive building shells with currently available model-specific simulation models cannot be estimated,

but general-use models, even more flexible, require a knowledge base at an expert level. Powersim Studio, which integrates the optimization module, is an appropriate modelling tool to determine or predict the performance of CABS. Powersim Studio, in comparison with other modelling tools, makes it easy and thoroughly comprehensible to create a building model that changes the value of the parameters during simulation.

9. Optimization is an essential part of the inverse modelling phase, which provides the best possible option defined by the user for the characteristics that characterize climate adaptive building envelope, which has an impact on energy performance and indoor comfort in buildings.
10. In the demonstrated research the facade design was reviewed from the energy performance perspective. The designers must find a compromise between the solar heat gain, daylight access and view from inhabitant’s perspective.

The hypothesis is confirmed – climate-adaptive building solutions contribute to achieving a zero-energy building level while maintaining good indoor microclimate.

REFERENCES

Andreasson, N., Anton E., and Patriksson, M. 2005. "An Introduction to Optimization : Foundations and Fundamental Algorithms."

Asere, L., Mols, T., and Blumberga, A. 2016. "Assessment of Energy Efficiency Measures on Indoor Air Quality and Microclimate in Buildings of Liepaja Municipality." *Energy Procedia* 95:37–42. doi: 10.1016/j.egypro.2016.09.009.

Boer, B. J., Ruijg, G. J., Roel Loonen, R., Trcka, M., Hensen, J. and Kornaat, W. 2011. "Climate Adaptive Building Shells for the Future – Optimization with an Inverse Modelling Approach." *European Council for an Energy Efficient Economy Summer Study* 1413–22.

Edmund Optics Inc. n.d. "Fresnel Lens Specification." Retrieved (https://www.edmundoptics.com/optics/optical-lenses/fresnel-lenses/5.0quot-x-5.0quot-2.8quot-focal-length-fresnel-lens/#downloads).

Energy Agency, International. 2013. *Policy Pathway to Secure Our Global Energy Future Modernising Building Energy Codes*.

ESP-r. n.d. "ESP-r, Multi-Platform Building Energy Software Tool." Retrieved (http://www.esru.strath.ac.uk/Programs/ESP-r_overview.html).

Favoino, F., and Overend, M. 2015. "A Simulation Framework for the Evaluation of next Generation Responsive Building Envelope Technologies." Pp. 2602–7 in *Energy Procedia*. Vol. 78. Elsevier Ltd.

Favoino, F., Overend, M., and Jin, Q. 2015. "The Optimal Thermo-Optical Properties and Energy Saving Potential of Adaptive Glazing Technologies." *Applied Energy* 156:1–15. doi: 10.1016/j.apenergy.2015.05.065.

GmbH Rubitherm Technologies. n.d. "Paraffin RT21 HC Data Sheet." Retrieved (https://www.rubitherm.eu/media/products/datasheets/Techdata_-RT21HC_EN_29062016.PDF).

Harish, V. S. K. V., and Kumar, A. 2016. "A Review on Modeling and Simulation of Building Energy Systems." *Renewable and Sustainable Energy Reviews* 56:1272–92.

Innova AirTech Instruments A/S. 1997. *Thermal Comfort*.

Kaliszewski, I., and Podkopaev, D. 2016. "Simple Additive Weighting—A Metamodel for Multiple Criteria Decision Analysis Methods." *Expert Systems with Applications* 54:155–61. doi: 10.1016/j.eswa.2016.01.042.

Kancane, L., Ruta, V., and Blumberga, A. 2016. "Modeling of Building Envelope's Thermal Properties by Applying Phase Change Materials." *Energy Procedia* 95:175–80. doi: 10.1016/j.egypro.2016.09.041.

Kasinalis, C., Loonen, R. C. G. M., Cóstola, D., and Hensen, J. L. M.. 2014. “Framework for Assessing the Performance Potential of Seasonally Adaptable Facades Using Multi-Objective Optimization.” *Energy and Buildings* 79:106–13. doi: 10.1016/j.enbuild.2014.04.045.

Kim, M. H., Jo, J. H., and Jeong, J. W. 2013. “Feasibility of Building Envelope Air Leakage Measurement Using Combination of Air-Handler and Blower Door.” *Energy and Buildings* 62:436–41. doi: 10.1016/j.enbuild.2013.03.034.

Kramer, R., Schijndel, J., and Schellen, H. 2013. “Inverse Modeling of Simplified Hygrothermal Building Models to Predict and Characterize Indoor Climates.” *Building and Environment* 68:87–99. doi: 10.1016/j.buildenv.2013.06.001.

Laicane, I., Blumberga, D., Blumberga, A. and Rošā, M. 2015. “Evaluation of Household Electricity Savings. Analysis of Household Electricity Demand Profile and User Activities.” Pp. 285–92 in *Energy Procedia*. Vol. 72. Elsevier Ltd.

Loonen, R. 2010. “Climate Adaptive Building Shells: What Can We Simulate?”

Loonen, R. C. G. M., Singaravel, S., Trčka, M., Cóstola, D. and Hensen, J. L. M. 2014. “Simulation-Based Support for Product Development of Innovative Building Envelope Components.” *Automation in Construction* 45:86–95. doi: 10.1016/j.autcon.2014.05.008.

Loonen, R. G. C. M., Trcka M., Cóstola, D., and Hensen J. L. M.. 2010. “Performance Simulation of Climate Adaptive Building Shells: Smart Energy Glass as a Case Study.” *8th International Conference on System Simulation in Buildings* 1–19.

Loonen, R. C. G. M., Favoino, F., Hensen, J. L. M., and Overend, M. 2017. “Review of Current Status, Requirements and Opportunities for Building Performance Simulation of Adaptive Facades.” *Journal of Building Performance Simulation* 10(2):205–23. doi: 10.1080/19401493.2016.1152303.

Ministru Kabinets. 2009. “MK Noteikumi Nr. 359 Darba Aizsardzības Prasības Darba Vietās, 28.04.2009.”

Moloney, J. 2011. *Designing Kinetics for Architectural Facades*. Routledge.

Mols, T., Dzene, K. P., Vanaga, R., Freimanis, R. and Blumberga, A. 2018. “Experimental Study of Small-Scale Passive Solar Wall Module with Phase Change Material and Fresnel Lens.” Pp. 467–73 in *Energy Procedia*. Vol. 147. Elsevier Ltd.

Mumovic, D. and Santamouris, M. 2009. *Sustainable Building Design and Engineering : An Integrated Approach to Energy , Health and Operational Performance*. London.

OECD. 2013. *Transition to Sustainable Buildings: Strategies and Opportunities to 2050*. Vol. 9789264202. Organisation for Economic Cooperation and Development (OECD).

Palonen, M., Hamdy, M. and Hasan, A. 2013. "Mobo a New Software for Multi-Objective Building Performance Optimization." *Proceedings of BS 2013: 13th Conference of the International Building Performance Simulation Association* 2567–74.

Powersim Studio 8 Academic (8.10.4916.6). n.d. *Powersim Studio 8 Help. Building Blocks in Powersim Studio*.

Sirmelis, R., Vanaga, R., Freimanis, R. and Blumberga, A. 2019. "Solar Facade Module for Nearly Zero Energy Building. Optimization Strategies." *Environmental and Climate Technologies* 23(3):170–81. doi: 10.2478/rtuect-2019-0087.

Stephan, L., Bastide, A. and Wurtz, E. 2011. "Optimizing Opening Dimensions for Naturally Ventilated Buildings." *Applied Energy* 88(8):2791–2801. doi: 10.1016/j.apenergy.2010.12.039.

Tawfik, M., Tonnellier, X. and Sansom, C. 2018. "Light Source Selection for a Solar Simulator for Thermal Applications: A Review." *Renewable and Sustainable Energy Reviews* 90:802–13.

Vanaga, R., Blumberga, A., Freimanis, R., Mols, T. and Blumberga, D. 2018. "Solar Facade Module for Nearly Zero Energy Building." *Energy* 157:1025–34. doi: 10.1016/j.energy.2018.04.167.

Wang, T., Seo, S., Liao, P., and Fang, D. 2016. "GHG Emission Reduction Performance of State-of-the-Art Green Buildings: Review of Two Case Studies." *Renewable and Sustainable Energy Reviews* 56:484–93.