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Faculty of Building and Civil Engineering

Heat, Gas and Water Technology institute

M.sc.ing Baiba Gaujēna

INFLUENCE OF MATERIALS' PROPERTIES OF BUILDING ENVELOPE ON INDOOR CLIMATE

Doctoral Thesis

Scientific Supervisor

Dr. sc. ing. prof.

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CONFIRMATION STATEMENT

Hereby I confirm that I have worked out the dissertation which is submitted for acquisition the degree of Doctor of Engineering Sciences at Riga Technical University. The dissertation has not been submitted in any other university for acquisition of scientific degree.

Baiba Gaujēna …………………………… (Signature)

Date: ………………………

The dissertation has been written in Latvian, it contains introduction, 6 chapters, conclusions, references, 63 figures and 24 tables. It composes 137 pages with 94 reference sources.

ANOTATION

The thesis constitutes an extensive study of heat flow and air permeability of building enclosures with an aim of ensuring optimal indoor microclimate. The thesis consists of three main parts: research of literature and a computational model regarding the effect of external wall structures on indoor microclimate, an experimental study, and the development of a computational model. The first part of the thesis examines earlier international studies regarding building enclosures and calculation methodology, and the existing moisture migration and heat flow calculation models for external wall structures, as well as the characteristics of building enclosure materials. In addition, a critical review of the regulatory documentation was conducted, and the concept of optimal microclimate was defined. The tasks for achieving the objective of the work were concretized in accordance with the researched information.

Based on the results of the research conducted during the work and taking into account the experimentally obtained results and the known calculation methods of thermal engineering processes, rooms were modeled with the help of finite element computational fluid dynamics software, selecting optimal indoor microclimate as the main parameter.

The following results were achieved in the course of the work:

- A model for calculation of heat flow processes in building enclosures has been developed and experimentally substantiated.
- Proposals have been developed for changes in the Latvian Construction Standard LBN 002-01 “Thermal Engineering of Building Envelopes” and LBN 231 “Heating and ventilation of buildings”.
- Substantiated application of building enclosure materials in various types of buildings has been developed and proven with the help of dynamic simulation software.

The objective of the thesis is to obtain results with scientific and practical application, as well as to provide answers to current questions related to ensuring optimal microclimate by taking into consideration the characteristics of building enclosures. The basis of the research is the scientific and technical hypothesis regarding the possibilities of increasing building construction and usage quality by taking advantage of the solidity characteristics of the structures.

The main results of the study have been reported in 12 international conferences and 15 publications. The thesis consists of 138 pages, including 24 tables and 63 figures. The bibliography includes 94 references.

CONTENTS

INTRODUCTION

A topic of increasing importance is the design and construction of new buildings not only by implementing more modern energy efficient solutions, but also by placing a greater focus on ensuring optimal indoor microclimate.

In order to retain heat and maintain a suitable indoor microclimate in buildings, it is necessary to ensure correct selection and applications of constructions in the design stage. The application of materials and constructions must be different in buildings of different types (residential buildings, public buildings or storage premises).

The topic of the thesis is connected with the need to develop a method and recommendations pertaining to the application of modern technical solutions and materials in construction, with an aim of ensuring optimal indoor microclimate depending on the characteristics of their application. Earlier studies have proven that the solidity of structures has a significant impact on the heat balance of buildings, but the studies lack specific data and measurements corresponding to climatic conditions with significantly variable temperature during the heating season.

By using mathematical modeling, it is possible to make calculations for various rooms in order to determine the stability of indoor air parameters. The air flow in the room and its intensity depends on the layout of objects, as well as on the thermal engineering properties of the building enclosure. However, by conducting modeling, it is possible to predict the actual situation, if it is based on parameters that have been previously substantiated experimentally.

Gendelis S. proved in 2012 that thermal engineering characteristics of buildings and structures that have been obtained experimentally and theoretically may significantly differ. However, computational modeling is based on taking into account all elements related to the building or structure – thereby making the results comparable to the actual conditions. The analysis developed in the thesis includes both methods that are already known and completely new approaches in the use of dynamic simulation software.

The *objective* of the work is to find materials suitable for the enclosures of residential buildings and to justify rational application thereof with study results.

Tasks:

- Research of the outdoor air parameters: temperature fluctuations and humidity content changes during the heating period.
- Research of various types of enclosures in existing buildings and buildings under construction, as well as the effect of the solidity of building enclosures on indoor microclimate; changes of their characteristics in various weather conditions.
- Development of recommendations for the ensuring of optimal indoor microclimate.
- Development of a computational modeling methodology that would allow determining the planned improvement of indoor comfort conditions.
- Approbation of the developed experimental measurement and computational modeling methodology.
- Analysis of the experimental results and the theoretically calculated results; analysis of the causes of differences.
- Analysis of the economic parameters of building enclosures.

The research as part of the thesis will continue earlier research by the Institute of Heat, Gas and Water Technology (HGWT) regarding building enclosures with adjustable thermal resistance and the effect of the solidity of building enclosures on indoor microclimate.

Optimal microclimate parameters and the effect of building enclosure materials on indoor air and humidity parameters have been previously research by scientists such as Prof., Dr.habil.sc.ing. A. Krēsliņš, Prof., Dr.habil.sc.ing. V. Zēbergs, Dr.habil.sc.ing. N. Zeltiņš, Prof., Dr.habil.sc.ing. K. F. Fokins, Doc., Dr.sc.ing. V. Vrubļevskis, Dr.sc.ing. A. Borodiņecs, engineering doctors D. Pupeikis (Kaunas, 2010) and S. Gendelis (Riga, 2012), as well as Asoc. Prof., Dr.habil.sc.ing. A. Jakovičs and Prof., Dr.habil.sc.ing. V. Stankevičius. Mathematical models for characterization of the thermal conduction process have been researched by Prof., Dr.habil.sc.ing. V. Barkāns.

1. ANALYSIS OF THE CLIMATIC CONDITIONS OF LATVIA

Latvia lies fully within the cold climatic zone, and therefore energy efficiency measures are very important and a large amount of thermal energy can be saved in this field.

The examined heating seasons differ: the number of degree days in the 2010/2011 heating season was 4337.6, in the 2011/2012 heating season: 3823.4 degree days, and in the 2012/2013 heating season: 4359.2 degree days.

At present, the average temperature of the five coldest days with a probability of 0.92 (-20.7 °C) is used in design calculations in Latvia, but meanwhile the average temperature during the heating season is 0 °C.

In order to more precisely determine the specifics of air parameters in Latvia, analysis was conducted regarding the distribution of temperature and the corresponding relative humidity percentage values by months in hours. The results are presented in charts (Figures 1 and 2). Months of the past there and a half years have been examined, from November to February.

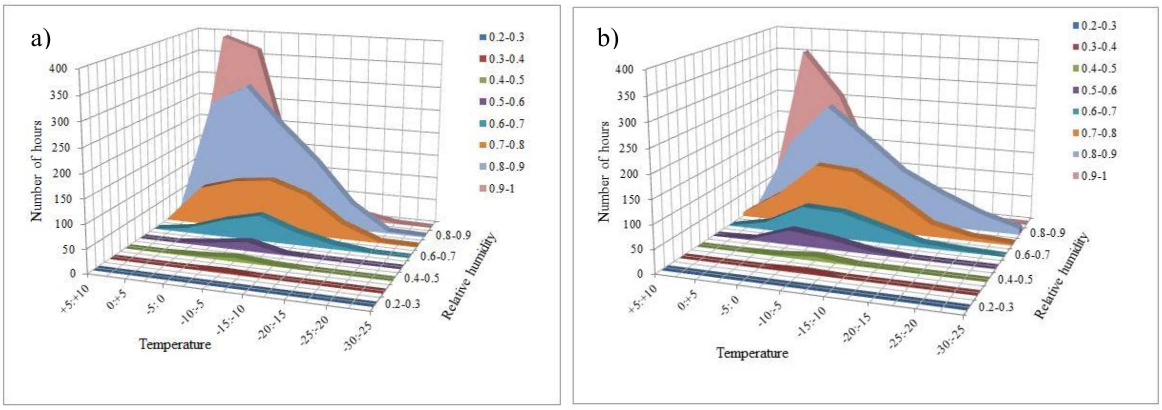

Figure 1. Number of hours in November (a) and December (b) at the respective temperature and relative humidity in the period from 2009 to 2013.

As Figures 1 and 2 demonstrate, the outdoor ambient temperature in Latvia was below the design temperature of the heating system for 150 hours during the five-year observation period – an average of 30 hours per year. The task of the building owner is to correctly determine the indoor air parameter stability requirements, and the designer must therefore select the optimal ratio of thermal mass and maximum capacity of the heating system.

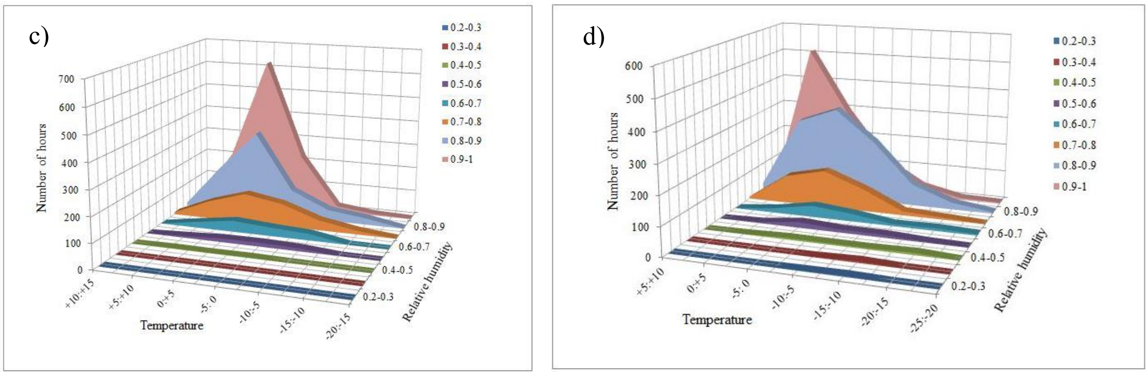

Figure 2. Number of hours in January (a) and February (b) at the respective temperature and relative humidity in the period from 2009 to 2013.

2. CHARACTERISTICS OF THE HEATING MODE OF BUILDINGS

Under the actual conditions, the building heating process is somewhat unstable, although it is based on real calculations in accordance with stable characteristic curves in the heating exchange process. In spite of all modern knowledge microclimate systems, following practical observations and theoretical investigations, undesirable fluctuations in the temperature scale take place when heating indoor premises. Such fluctuations have a negative impact on indoor comfort, and they create an incorrect impression of the energy consumption requirements of the building.

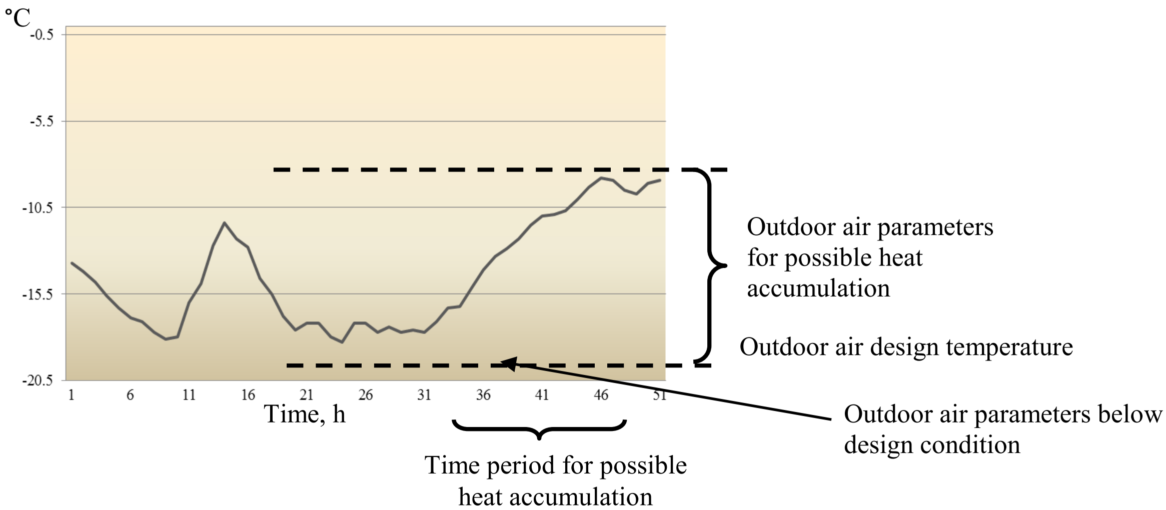

Figure 3. Outdoor temperature fluctions for January 2013.

Figure 3 shows outdoor air fluctuations in the winter period in Latvia, when temperature fluctuations even within a single day can reach ±10°C, but do not fall even to the design temperature of the heating system.

Unnecessary building energy consumption is observed in the course of incorrect maintenance of buildings. The cause of excessive heat flow is excessive thermal capacity and overheating of the building, which is related to the installation of equipment with inadequate (insufficient) heat capacity, manifesting in an excessively long pre-heating process. It leads to incorrect maintenance of buildings, as it is difficult to maintain a stable indoor climate conforming to all hygiene requirements. Due to these reasons, saving of energy has an impact on human health.

Theoretical evaluation of heat inertia on indoor air parameters stability

For the theoretical evaluation of heat inertia on indoor air parameters' stability the model of one floor building has been chosen. The floor area is 100 m^2, height of the building is 3m and wall area is 110 m^2 and window area – 20 m^2. Air infiltration is not taken into account in this evaluation. Three different types of external building envelope were evaluated. In all evaluated cases in addition to external wall there was floor on the ground with U = 0,3 W/m^2k and flat roof with U = 0,2 W/m^2k.

Initially it is assumed that indoor temperature is (-20,7 ^oC), indoor temperature is +22^oC and maximum heating boiler capacity is at (-20,7 ^oC) . In case of steady heat flow the heat loses will be the following:

$$Q = H_T(t_i - t_e) = 145 \cdot (22 - (-20{,}7)) = 6174W$$

In case when outdoor temperature drops till (– 34,9 ^oC) heat losses will be 8386Wh. A simple calculation shows that for steady heat flow the indoor temperature will be:

$$t_i = \frac{Q}{H_T} + t_e = \frac{6174}{145} + (-34{,}9) = 7{,}7 \approx 8^\circ C$$

As it can be seen form Table 2 the walls made from masonry or lightweight concrete blocks have heat inertia three times higher than timber-frame construction with insulation. Obviously the indoor temperature and surface temperature reduction in heavy construction will be slower than in timber-frame construction. In order to evaluate cooling time of indoor space it is necessary take into account thermal mass. The time of temperature drop can be calculated using the data:

$$t = t_o e^{-\frac{H}{w}} + (t_e + \frac{Q}{H})(1 - e^{-\frac{H}{w}}), \qquad (1)$$

where H building transmission heat losses, W/K; Q - heating system's heat production, W; w - heat gains from heat accumulate by building envelope and furniture, W.

In order to evaluate time of indoor temperature drop in building theoretical model for three different building envelopes the equation 1 and materials' properties data where used. It is assumed that capacity of heating boiler is designed for outdoor temperature (-20,7 ^oC) and outdoor air temperature drops from (-20,7 ^oC) till (-34,9 ^oC). The results are presented in Figure 4.

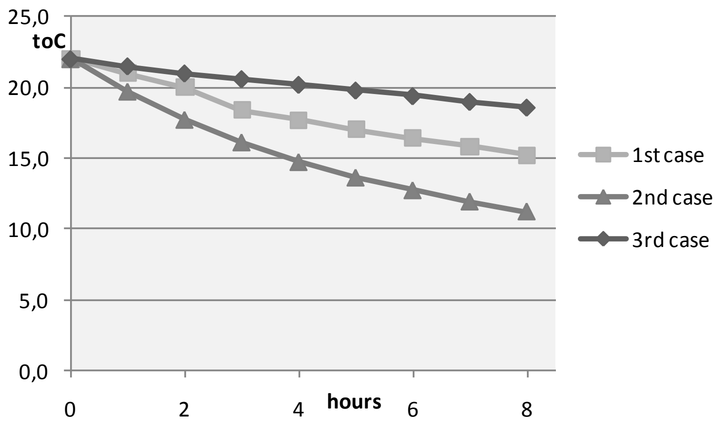

Figure 4. Indoor temperature reduction for three different types of building envelope, in case what outdoor temperature drops till (-34,9^oC).

As it can be seen form Figure 4 the indoor temperature drops during the first eight hours by the 10,8 ^oC for timber-frame structures; by 6,8 ^oC for lightweight concrete block and by 3,4 ^oC for brick wall with insulation.

As it was expected, the temperature reduction has been more rapid for construction with smaller thermal inertia. The typical outdoor design temperature cannot ensure indoor air parameters stability for the lightweight building envelopes. This issue is of special importance for such specific buildings like hospitals and museums where it's vitally important to ensure indoor air parameters stability at any outdoor air conditions.

At the same time, use of the absolutely minimal outdoor air temperature for calculation of heating systems' capacity leads to decreasing of heating systems' operation efficiency during the whole heating season. Proper balance of building thermal mass and heating systems' maximal capacity gives the possibility to ensure indoor air parameters stability at extremely cold outdoor air temperatures and to improve operation efficiency of heating systems.

3. THE STACK EFFECT INFLUENCE ON AIR EXCHANGE RATE AND IAQ IN DWELLING BUILDINGS

The main aim of ventilation systems in dwelling buildings is to ensure optimal comfort conditions and indoor air quality for inhabitants. While temperature and humidity level are crucial indicators for human comfort, CO_2 concentration is significant factor for human health. The air-exchange rates in dwelling buildings commonly are calculated by the same methods irrespective of the apartment's level. This research is devoted to modeling of CO_2 concentration in indoor air and air distribution in multi-storey apartment buildings. A stack effect could be observed in the multi-storey buildings during the winter. When internal walls, ceilings and HVAC shafts are not airtight, in addition to heat circulation, CO_2 and moisture circulation from building's lower levels to upper levels is also taking place. In such case the amount of air-exchange rate and ventilation scheme should differ for upper and lower building's levels. The results provides of IAQ features in multi-storey dwelling buildings paying particular attention to the influence of building's level and airtightness of buildings' internal elements on IAQ parameters.

Nowadays during the construction of new buildings and the renovation of the existing ones in Latvia the mechanical exhaust from kitchens and bathrooms is commonly used and natural air supply is acquired through the simple air inlets in bedrooms or event by opening the windows. In some cases natural ventilation also is used in dwelling buildings. It is incontestable that during the winter air infiltration is acquired through the lower levels of the building and exfiltration – through the upper levels. So the infiltration and exfiltration process makes difficult the exploitation of natural and mechanical/natural ventilation systems. Existing research on indoor air quality in high-rise residential building (Jungmin, 2010) has shown the specifics of CO_2 concentration for three different types of ventilation systems. This research has shown that CO_2 concentration in upper levels is up to 1,9 times higher than for lower levels. This effect is explained by smaller air infiltration rate for upper floor.

A lot of work was done in order to improve airtightness of buildings' external envelope. But at the same time there is no common developed theoretical methodology of evaluation of impact of air leakage on building performance in building design stage. The strict gradation exists only for windows air leakage LVSEN (2001). But for external walls and roof structures theoretical evaluation of air leakage is problematic due to the lack of information on air permeance of building materials. The existing studies SP (2008) and (Rousseau, 2008) present data only for limited number of building materials.

In addition the airtightness of buildings' internal elements should be evaluated and estimated in order to reduce air overflow from lower levels to higher levels.

Methods

The level of infiltration and exfiltration in building depends on stack effect and wind pressure.

Total impact of stack effect and wind pressure on infiltration of buildings floors can be found using the following equation

$$\Delta P = 0.5H(\rho_e - \rho_i)g - h(\rho_e - \rho_i)g + 0.5\frac{\upsilon^2 \rho_e}{2}K(c_h - c_z), \tag{2}$$

where H – height of the building, m; $\rho_e ; \rho_i$ – outdoor and indoor air density, kg/m^3; h – distance from ground to the center of the considered element, m; υ – wind average speed, m/s; K – wind speed correction factor, which depends on type of terrain; c_h – value of the aerodynamic coefficients on the windward side, c_z – value of aerodynamic coefficient on the leeward side.

For the theoretical evaluation of air ventilation rate impact on the CO_2 level, the theoretical model was developed on the basis of mass and energy balance.

As the result the concentration of indoor air CO_2 level can be calculated using the following formula:

$$c_i(t) = c_e + (c_0 - c_e) * e^{-n*t} + (1 - e^{-n*t}) * \frac{n_{pers} *q}{n*V}, \tag{3}$$

where V – room volume,m^3; n – air exchange rate, c_e – outdoor air $C0_2$ concentration, kg/m^3, n – number of persons in room; q – CO_2 production by one person, kg/h, c_i – indoor air CO_2 concentration, kg CO_2/m^3, c_o – initial indoor air CO_2 concentration, kg CO_2/m^3.

Results

For the purpose of practical evaluation of IAQ, two similar apartments on the 1st and 9th floor were analysed in the same building (Figure 5). The area of all analysed bedrooms is 14 m^2 and volume – 36 m^3. The ventilation system consists of central mechanical exhausts from kitchens and natural air supply in bedrooms through regulated air inlets. The flow level through air inlets is regulated manually. The diameter of air inlet is 100 mm. Each bedroom is occupied during the night by two adults and one infant. The roof exhaust ventilator was not operating at night during the study. All bedrooms' windows are situated on the northern façade. For the nine-storey apartment building the air pressure difference in Latvian climatic conditions (LBN003 2001) is shown in table 1.

Table 1. The air pressure difference for nine-storey apartment building calculated from equation 1 using average Latvian climatic conditions, ΔP, Pa

Table1.

Floor \ Mon.	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
1.st.	23	21	19	15	11	9	7	8	12	16	21	23
9.st.	-1	-3	-1	1	2	4	4	4	4	4	3	1

Typically dwelling buildings up to 16 floors are built from concrete panel with stone wool (or glass wool) heat insulation and with concrete external finishing. Basing on data SP (2008) the resistance to infiltration can be calculated:

$$R_{\inf} = R_{\inf}^{concrete} + R_{\inf}^{insulation} + R_{\inf}^{ext.fin}, m^2 hPa / kg, \quad (4)$$

where $R_{\inf}^{concrete}; R_{\inf}^{insulation}; R_{\inf}^{ext.fin}$ – resistance to infiltration of concrete panel, insulation and external finishing, m^2hPa/kg (the values of resistance to infiltration for different building).

The resistance to infiltration of an external wall: $R_{\inf} = 39242 m^2 hPa / kg$. Such high resistance to infiltration does not have any impact on total building's energy performance and quality of indoor air. The air tightness of windows still should be taken into account. The windows with resistance to air leakage R_{inf} = 0,65 kg/(m^2h) are typically used in Latvian market for dwelling building construction.

The level of infiltrated air through the windows is 2.68 kg/(m^2h) for 1st floor and 0,33 kg/(m^2h) for 9th floor. So the infiltration level for 1st floor is eight times higher than for 9th floor.

The total amount of infiltrated air during the night per room or per apartment can be expressed as following:

$$L = G_0 F + L_{a.i}, m^3 / h, \quad (5)$$

where $L_{a.i}$ – supplying air through air inlets, m^3/h, G_o – window's level of infiltration, kg/m^2h, F – window's area, m^2.

Amount of infiltrated air for one room on the 1st floor through one window and one air inlets is L = 62 m^3/h. Amount of infiltrated air for the 9th floor is L = 2.50 m^3/h.

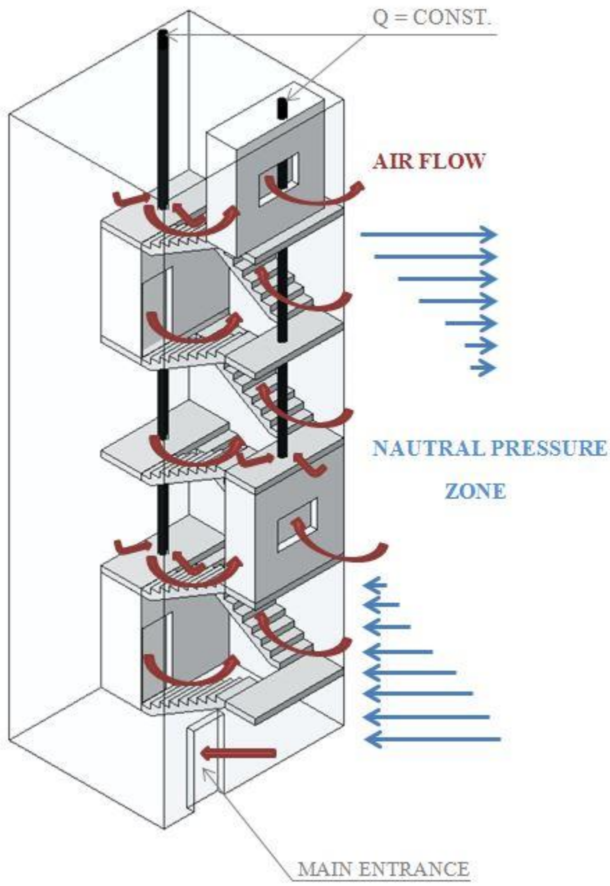

Figure 5. Air distribution in for nine-storey apartment building.

The theoretical air supply for the 9th floor is 25 times smaller than for the 1st floor. The exhausts ventilator capacity in 1st and 9th floor is 50m^3/h. Infiltrated air amount in 1st floor bedroom is 62 m^3/h. The difference between infiltrated and exhaust air volume for the room on the first floor is 12 m^3/h. That means that 12 m^3/h from 1st floor exfiltrates through door to the staircases and cracks in communication shaft and under the stack effect goes to the upper floors.

The measurements had shown that the CO_2 level on the 1st floor is significantly lower than on the 9th floor and did not exceed 1700 ppm. During the measurements the CO_2 level during the night time was up to 2500 ppm on the 9th floor. The relative humidity on the 1st floor varied from 30% till 50%. Also CO_2 concentration on the 9th floor was much higher during the night time and it dropped down after the opening of the window. But the ventilation by means of window opening has significant shortcomings due to high infiltration of cold outdoor air which can cause colds.

Theoretical simulation of CO_2 concentration was done using the equation 5. The comparison of measured and theoretical 9-hour fluctuation of CO_2 for the first floor is shown in figure 6. The figure presents part of measurements for bedroom, occupied by two adults and a child from 10.00pm. During the measurements outdoor air CO_2 concentration was 640 ppm.

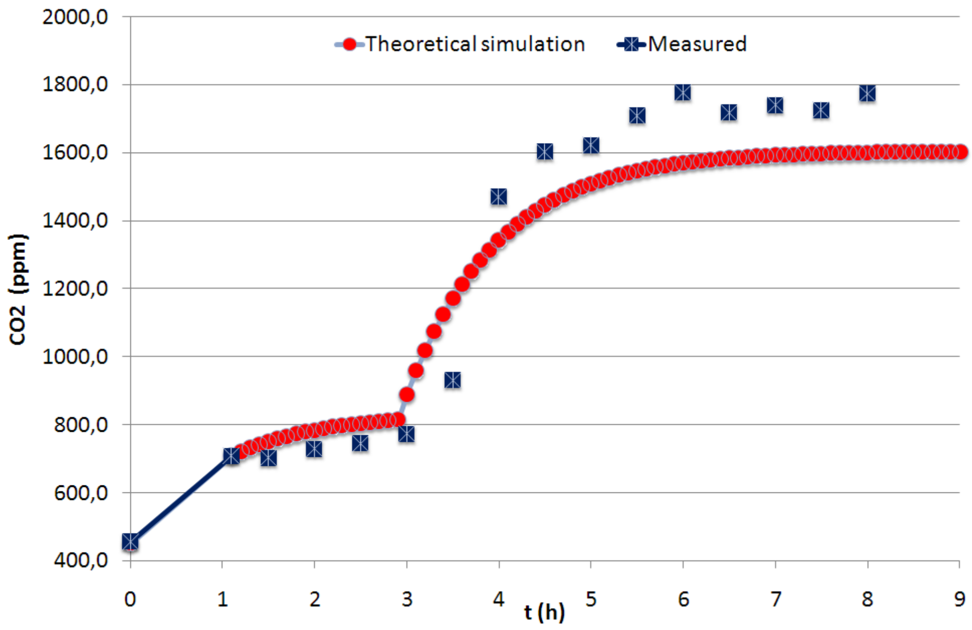

Figure 6. The comparision of measured and teoritical 9-hour fluctuation of CO_2 for the first floor.

4. EXPERIMENTAL STUDY ON THE EFFECT OF BUILDING ENCLOSURES ON HOME MICROCLIMATE

Fifty buildings were selected for the experiment, dividing them into two groups: lightweight construction buildings and massive construction buildings. For each building, measurements were conducted during the winter period from 2009 to the winter months of 2013. The heat consumption of the buildings was assessed during the work. For the purposes of the study, data were obtained from heat supply organizations regarding the heat consumed during the heating season, while building owners and other public institutions provided information regarding the number of inhabitants and technical information regarding the building enclosures. In analyzing the data obtained in each building group, measurements of the building enclosures and measurements of indoor ambient temperature and air humidity were conducted for each building by installing two measuring instruments: Testo 635-2 at the building enclosures and Testo 175-H2 in the middle of the room.

The total area of the described lightweight construction buildings is 235.8 m^2, the total area of the massive construction buildings: 8684.3 m^2.

To analyze the measurement data in real conditions, the work process involved the use of simulation software Computational Fluid Dynamics (CFD) Autodesk Simulation CFD 2013, which is based on a process that combines the real conditions with mathematical calculations. The software allows assessing activity by using modeling. The simulation software uses extensive calculations to ensure that the final result is as close as possible to real conditions.

Example of a lightweight construction building:

The enclosure of the lightweight construction house has been renovated with a heat insulation layer. The construction of the load-bearing walls consists of 180 mm thick wood beams with ecowool cladding and a 50 mm stone wool heat insulation layer on a framework of 5 cm thick planks on the outside. The interior lining consists of a single layer of plasterboard, the inside: painted plaster on a grid. Three people inhabit the room where the measuring instruments have been placed.

The data of the study, divided by measurements conducted throughout the day, are presented in tables and charts depicting the obtained measurement values of every 10 minutes.

Using the obtained results, it can be calculated that the average thermal transmittance value of the external building enclosure during the study was 0.285 W/m^2K, which conforms to the standard in accordance with Paragraph 14 of LBN 002-01.

According to the calculation, the thermal resistance of the wall R_t = 5.089 m^2K/W, while its heat transfer coefficient U = 0.196 W/(m^2K). The experimental data differ.

During the study, outdoor ambient temperature ranged from -5.2 °C to +2.7 °C, and the difference between the wall internal surface temperature and the indoor ambient temperature was 0.68 or 3.7%. Indoor relative humidity fluctuated from 35.1% to 42.08%, which is an acceptable range for human comfort.

Indoor ambient temperature during the study fluctuated by as much as 5.8 °C, which is a relatively large range, and the fluctuations are frequent, which is dictated by the outdoor ambient temperature and may cause discomfort to the people in the room.

The results presented in the Figure 7 show that, with the outdoor ambient temperature increasing, the indoor ambient temperature increases as well. The chart also shows that an increase of outdoor ambient temperature is accompanied by an increase in surface temperatures, and that surface temperatures fluctuate in proportion to the fluctuations of outdoor ambient temperature.

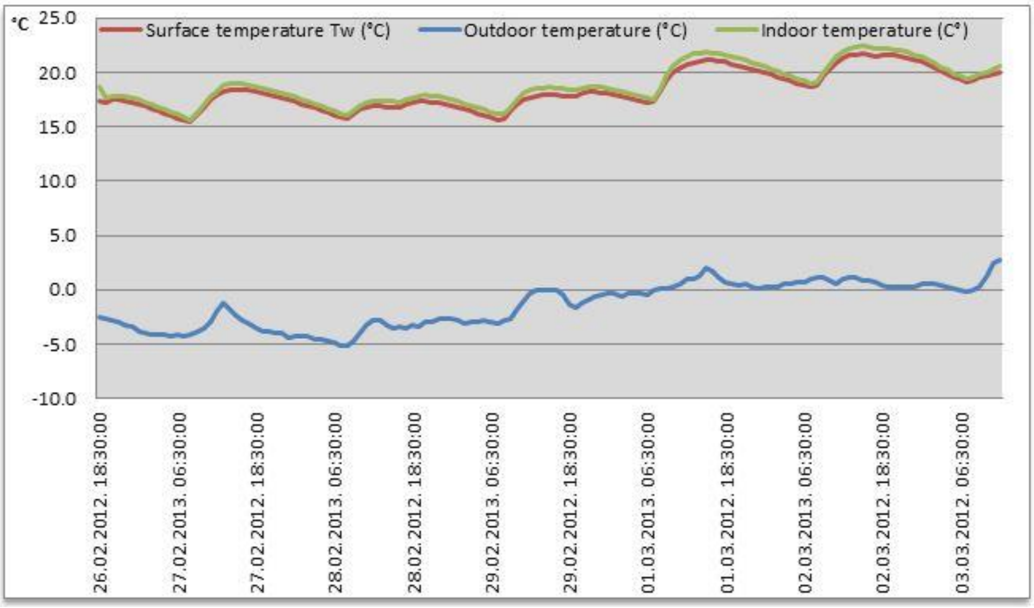

Figure 7. Fluctuations of surface temperature and indoor ambient temperature depending on outdoor ambient temperature.

Upon comparing the data obtained during the practical study with the data obtained through calculations, it can be concluded that the obtained U values differ. The heat transfer coefficient obtained in the study: U = 0.285 W/m^{2}K; in the calculation: U = 0.196 W/m^{2}K (a difference of 31%). It could be explained by possible cavities in the walls of the building due to improper filling with ecowool heat insulation during the renovation in 2009.

The software Autodesk Simulation CFD 2013 was used to simulate a model corresponding to the characteristics of the building with the experimentally obtained data and in accordance with the previously described selection of the room model.

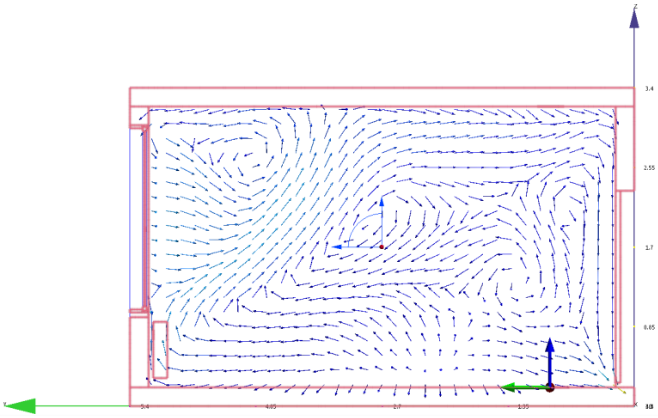

Figure 8. Air flow direction in the room.

Air flow in the building is shown with the help of vectors and corresponds to actual indoor air flow exchange.

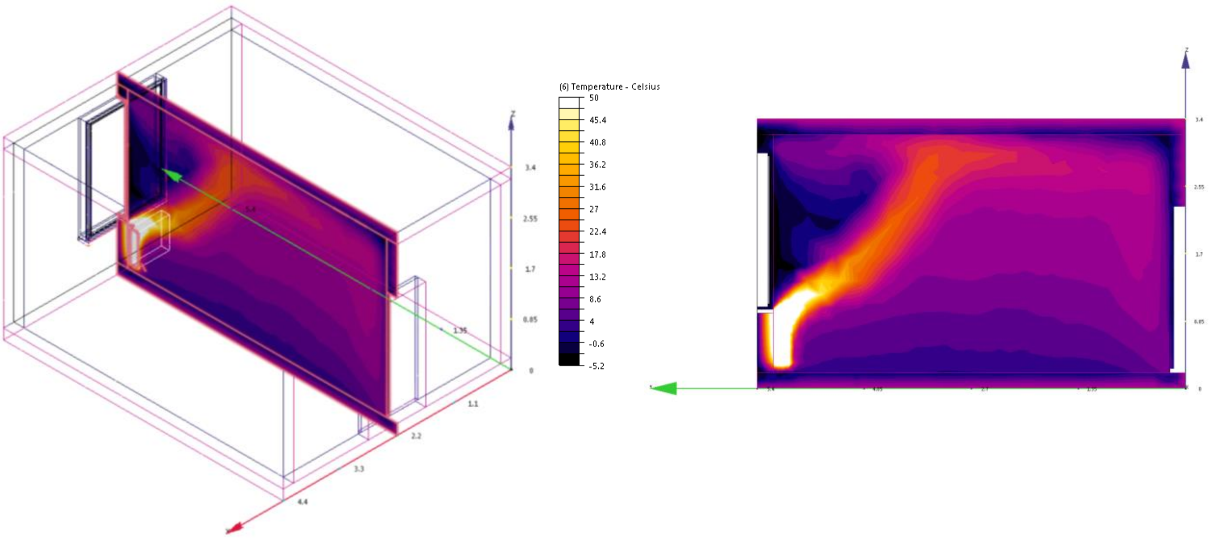

Figure 9. Indoor temperature distribution in 3D format and on a 2D plane.

Example of a massive construction building:

The enclosure of the massive construction house is cast reinforced concrete with a heat insulation layer. The load-bearing wall of the building consists of 300 mm thick cast reinforced concrete with a 100 mm thick insulation layer of stone wool. The interior lining is a single layer of plaster; on the outside: painted plaster on a grid. Three people inhabit the room where the measuring instruments have been placed.

The data of the study, divided by measurements conducted throughout the day, are presented in tables and charts depicting the obtained measurement values of every 10 minutes.

Using the obtained results, it can be calculated that the average thermal transmittance value of the external building enclosure during the study was 0.211 W/m^{2}K, which conforms to the standard in accordance with Paragraph 14 of LBN 002-01.

The table shows that, in accordance with the calculation, the thermal resistance of the wall R_t = 3,053 m^{2}K/W, while its heat transfer coefficient U = 0.328 W/(m^{2}K); the experimental data differ.

During the study, outdoor ambient temperature ranged from -10.1 °C to +5.9 °C, and the difference between the wall internal surface temperature and the indoor ambient temperature was 1 or 5.1%. Indoor relative humidity ranged from 31.4% to 51.7%, which is an acceptable range for human comfort.

Indoor ambient temperature during the study fluctuated by 2.9 °C, which is a small range, and the fluctuation period was gradually rising or falling depending on the surface temperature; consequently, a person staying in the room feels comfortable.

The results presented in Figure 10 show that surface temperature remains almost unchanged upon the outdoor ambient temperature increasing, and although outdoor temperature fluctuations are fast, an even surface temperature is maintained.

Upon comparing the data obtained during the practical study with the calculated data, it can be concluded that the obtained U-values differ. The heat transfer coefficient obtained in the study: U = 0.211 W/m^{2}K; in the calculation: U = 0.328 W/m^{2}K (a difference of 36%). It could be explained by the thickness values of the building structures; the greater they are, the lower the accuracy of the measuring instruments, which calculate the heat transfer coefficient based on the temperature difference and the wall thickness.

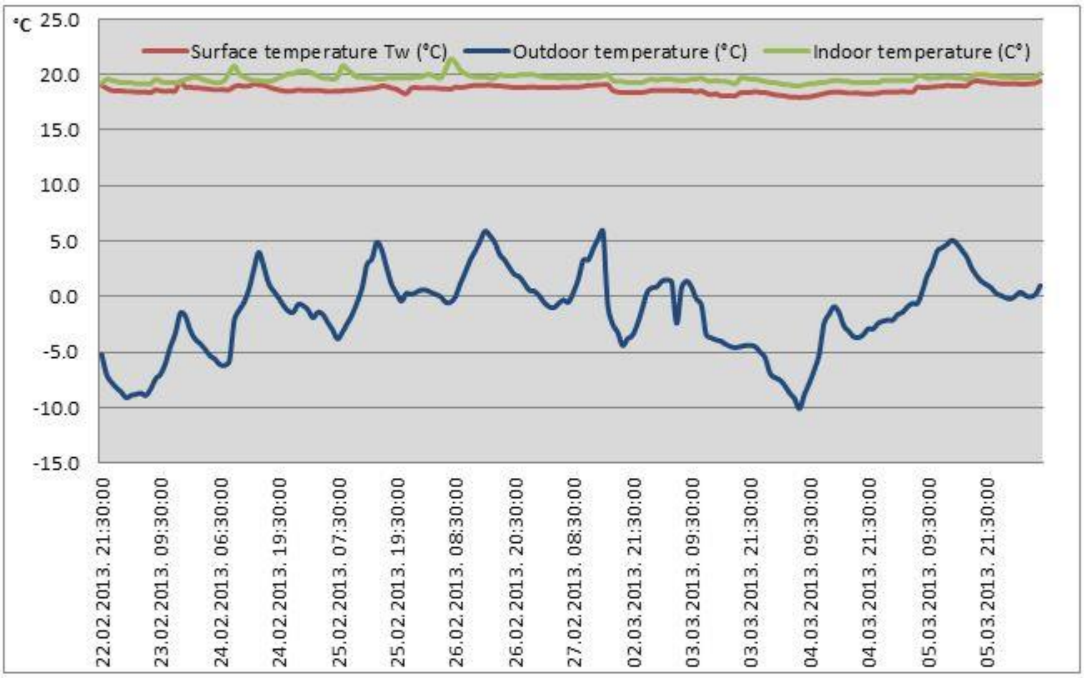

Figure 10. Fluctuations of surface temperature and indoor ambient temperature depending on outdoor ambient temperature.

A model was simulated in Autodesk Simulation CFD 2013, using the experimentally obtained data and in accordance with the previously described selection of the room model, corresponding to the characteristics of this building. Temperature fluctuations and value in the middle of the room: at outdoor ambient temperature -5.2 °C.

As the chart shows, heat flow is variable in the middle of the room, which evidences constant movement of the warm air following the air flow vector lines. However, temperature in the middle of the room in accordance with the model has been modeled precisely and corresponds to the experimental measurement: -19.4 °C.

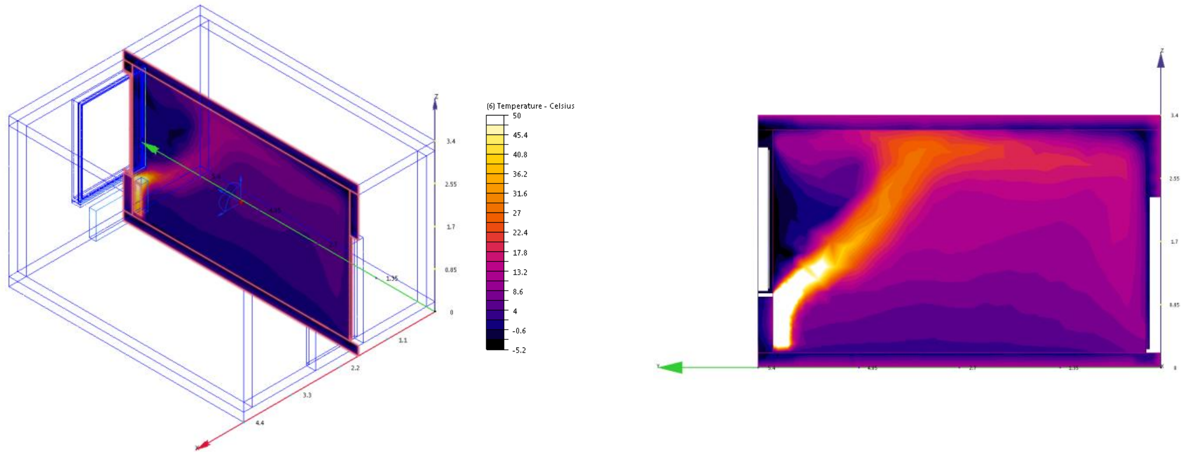

Figure 11. Indoor temperature distribution in 3D format and on a 2D plane.

Development of the implementation of the variation coefficient of the heating system, taking into consideration the solidity of buildings

The thermal stability of a room is the ability to reduce indoor ambient temperature fluctuations upon fluctuations in the heat flow of the heating system. The smaller the fluctuation range of ambient temperature in the room at the same conditions, the more stable it is.

Thermal stability is most linked with the solidity of the building enclosure; if the wall is more massive, it maintains heat better. The lower the inside surface temperature changes at the same ambient temperature range, the more stable it is, and vice versa.

As the acceptable range of temperature fluctuations is ± 3 °C, using previously experimentally proven data, it can be assumed that this value for premises with lighter enclosures fluctuates within a much larger range than for massive enclosures.

Heat transfer rate fluctuations of the heating device are assessed based on the variation coefficient m, which is determined in accordance with the formula

$$m = \frac{Q_{\max} - Q_{\min}}{2Q_z}, \tag{6}$$

where Q – the maximum heat transfer rate of the heating system, Wh; Q – the minimum heat transfer rate of the heating system, Wh; Q – the average heat transfer rate of the heating device, Wh.

The value m depends on the heating system and its operation. The coefficient m has a great significance in determining the indoor temperature fluctuation range, i.e., in assessment of the indoor thermal stability.

It was previously believed that, if district heating is used, the value of the coefficient m is 0.1, but in finite element computational dynamics software, it was proven that the coefficient varies both at different temperatures and depending on whether the external wall is lightweight or massive. The obtained results are presented in Table 2.

In order to determine a more accurate value of the variation coefficient, like before, a model was simulated with the effect of external weather conditions – Figure 12.

Tabele 2.

Calculation values of coefficient *m* at various outdoor ambient temperature values.

T °C / Construction	0 – -10 °C	-10 - -15 °C	-15 - -20.7 °C
Light weight construction	0,06	0,20	0.30
Masive wall construction	0,10	0,23	0,36

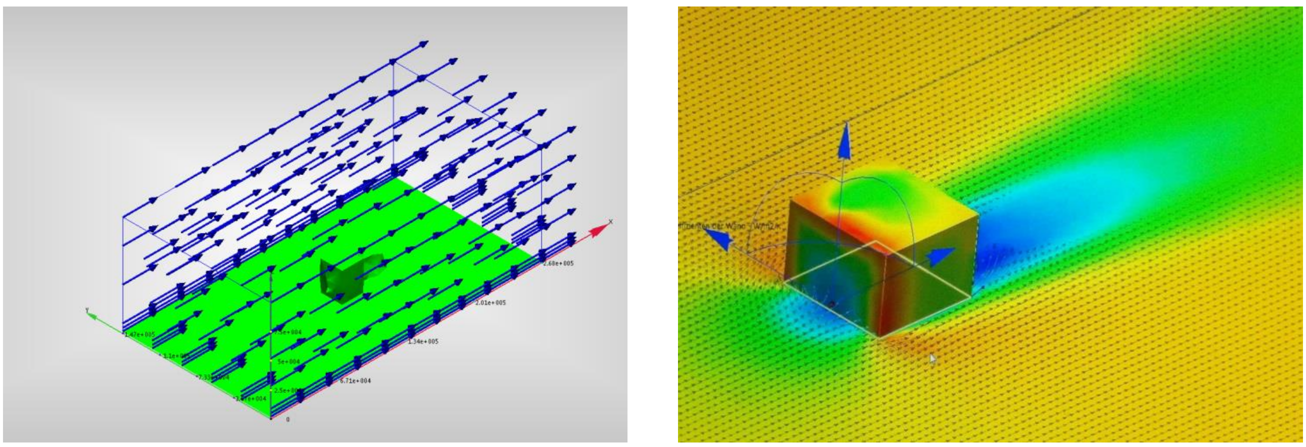

Figure 12. Determination of wind pressure and temperature in the model.

5. ASSESSMENT OF FINANCIAL EFFICIENCY

In order to determine the cost savings achieved by using certain building enclosure materials, buildings with two different external wall constructions were selected. After assessing the existing building structures, a building with a living space of 150 m^2 and ceiling height of 2.7 m was selected for the model. The analysis used experimentally obtained measurement data regarding the wall structures and the amount of heat (kWh/m^2) consumed for heating of the respective building in 6 months of last heating season. It was assumed for both buildings that district heating is used and the present costs per MWh have been compared, the costs correspond to the average price in the Latvian market.

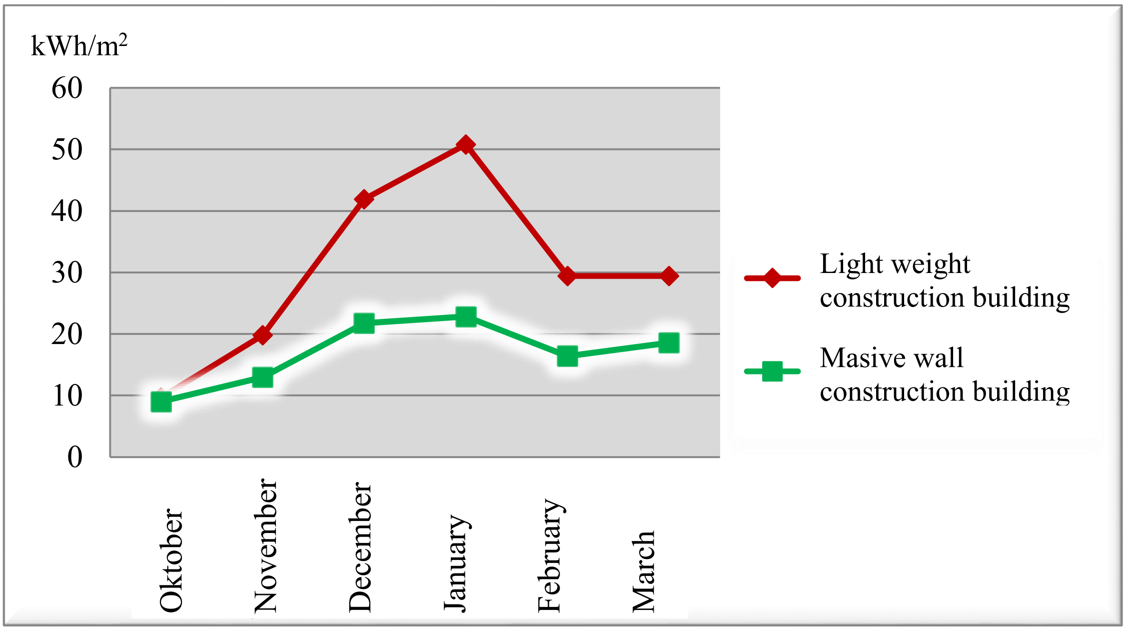

Figure 13. Building thermal energy consumption (kWh/m^2) in the 2012/2013 heating season.

$$NPV = \sum_{n=0}^{N} \frac{R_t}{(1+D)^n} = \int_{n=0}^{\infty} (1+D)^{-n} r(n) dt \,, \qquad (7)$$

where Rt – cash flow, EURO; D – discount rate, %; n – each subsequent year in the recoupment period.

Taking into account the discount rate, the recoupment period differs from the previously estimated 12 years. At the net present value, the project is recouped in the 32nd year, but, taking into consideration the time of use of the building, this period proves the efficiency of the project in any case.

The chart (Figure 14) displays the differing growth trend of net profit and net present value; the net savings rapidly increase already in the first years and continue increasing, while the net present value curve grows faster in the first years, and with each following year the growth declines proportionally.

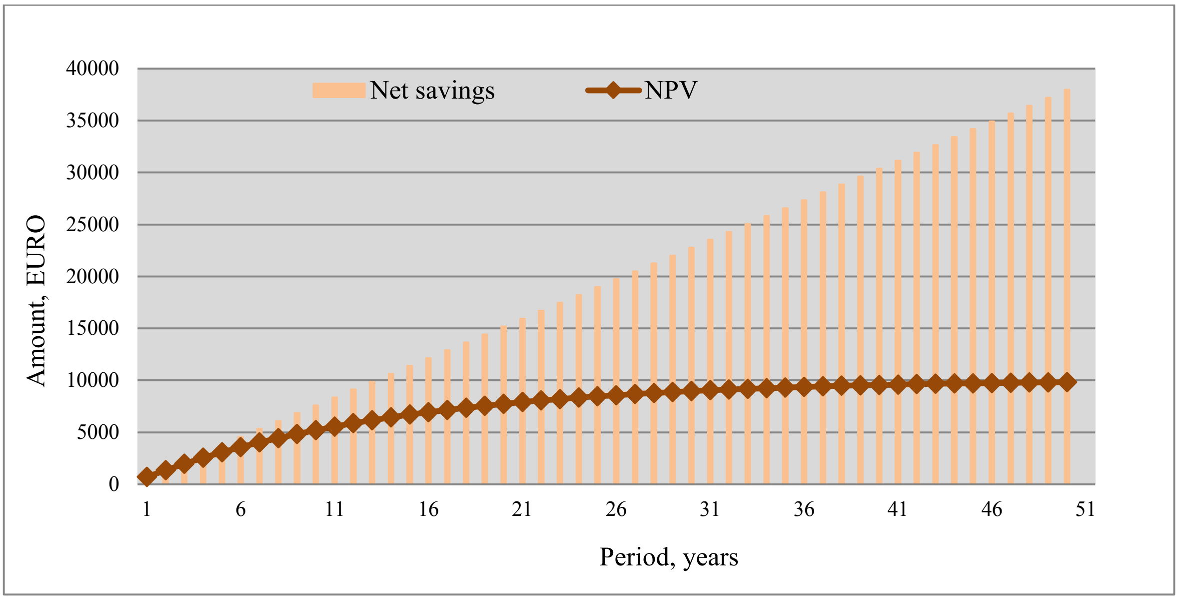

Figure 14. Comparison of present value and NPV cash flow in 50 years.

The recoupment period of the project is depicted in the chart (Figure 6.4). It shows that costs until the 32nd year are negative, but after the end of the recoupment period, the curve changes orientation, and the project becomes profitable.

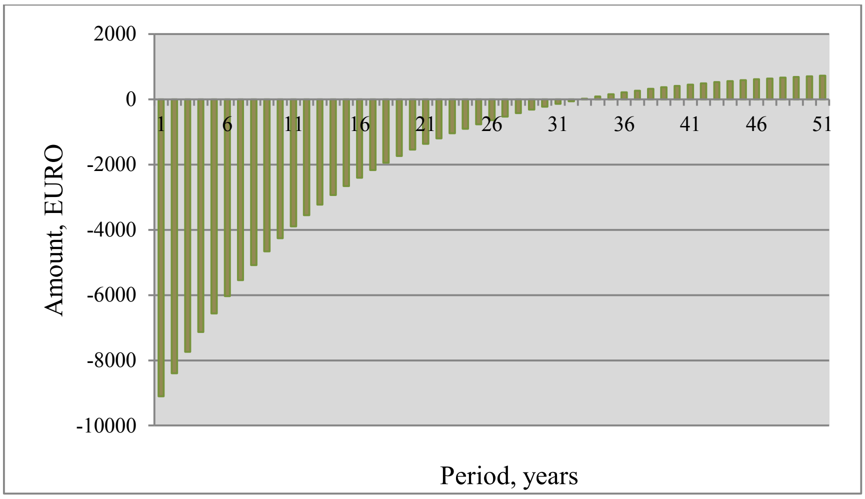

Figure 15. Recoupment period.

In spite of a much greater initial investment, massive construction buildings are more economical. When examining these structures over a longer period, they offer a longer life, greater stability and safety, both from the structural standpoint and in terms of fire safety. As a result, it can be concluded that massive building enclosures are more cost-effective and safer when looking at the lifespan and quality of the building.

CONCLUSIONS

1) The requirements of Latvian Construction Standard LBN 002-01 "Thermal Engineering of Building Envelopes" regarding the air permeability of a building and the thermal inertia of building elements are incomplete and make it appear as if these parameters are insignificant in the thermal engineering calculations of building enclosures. It has been proven in practice that they have a great impact on reducing the energy consumption of the building and ensuring a stable indoor microclimate.
2) Latvian Construction Standards LBN 002-1 "Thermal Engineering of Building Envelopes" and LBN 231 "Heating and ventilation of buildings" are not mutually harmonized, which makes it difficult to conduct optimal research of the effect of construction material characteristics. Because of that, there is no clear methodology concerning the impact of the solidity of the construction on the heating system assessment. As a result, buildings are built without taking into consideration the properties of the enclosure materials and their characteristics in practical application.
3) The outdoor ambient temperatures provided in standards significantly differ from those observed during the study; for example, the 50-year maximum temperature of -34.8 °C and 10-year temperature of -31.0 °C, which is sometimes used in calculations to determine the capacity of a heating unit, was not observed during any of the analyzed heating seasons.
4) Upon analysis of climatic data, it was found that the most frequently used heating system design temperature of -20.7 °C was observed twice in three heating seasons during the study, which indicates an inefficient calculation of the heating system.
5) The Latvian construction standards do not define microclimate; only explanatory information can be found in Cabinet Regulation No. 359. However, the regulation does not define an important parameter such as the maximum CO_2 content.
6) People in a room may have a different reaction to microclimate changes and conditions; it depends on each individual's personal preferences, as well as the clothing and the level of activity. For example, if a person in a room is working while sitting in long-sleeved clothing, the desirable temperature is +22°C; if the conditions are the same but the person is lying down, the comfort temperature increases to +26°C; when exercising in the room, it drops to +16°C.
7) The theoretical assessment of indoor air stability shows that rapid decline of temperature takes place in buildings with a low thermal inertia (D=1.44), for example, in buildings with a wood frame. For wood frame buildings, the absolute minimum temperature (once per 50 years) must be used, with minimum permissible fluctuations of indoor air temperature and relative humidity.
8) Depending on the indoor heat increase, the thermal mass of the building and the requirements pertaining to indoor air parameters, the following outdoor design temperatures may be used for calculation of the maximum thermal capacity of heating systems: the average temperature of the five coldest days (probability: 0.92), the average temperature of the five coldest days (probability: 0.98), the absolute minimum temperature (once every 10 years), the absolute minimum temperature (once every 50 years). The subsequent study will reveal the interrelations of all aforementioned factors. Even in the case of a building with a high thermal mass and minimum indoor air parameter requirements, the outdoor design temperature could be higher than the average temperature of the five coldest days (probability: 0.92).

9) Calculations of the ventilation system and the air exchange rate are usually conducted without taking into consideration the level of the apartment – even though the air pressure difference between the first and the ninth floor in a nine-story apartment building is 24 times. It was proven in the course of the work that it is necessary to design ventilation systems while accounting for the number of floors and the location of the apartment.
10) Even if the overall balance of supply air and exhaust air has been calculated correctly, there is a risk of air overflow due to infiltration. In such a case, additional air exfiltration takes place in staircases and cracks in ducts, and it rises to the upper floors.
11) The impact of air infiltration on energy consumption and indoor air parameters is very important for high-rise buildings, as demonstrated by the example of a nine-story apartment building; the air infiltration on the first floor is 62 m^3/h, but on the ninth floor: 2.50 m^3/h.
12) Heat radiation has a great impact on indoor microclimate. For example, if the indoor ambient temperature is +25 ºC, which corresponds to very comfortable conditions, but the internal surface temperature of the enclosure is a low +10ºC (the surfaces are cold), the radiation of the cold surfaces creates significant heat losses.
13) The indoor temperature fluctuation range for massive constructions is ± 4 °C, for lightweight constructions: ± 6 °C. The fluctuation range of massive constructions also exceeds the permissible range of ± 3 °C, but only by one degree, which might not be felt in practice, while for lightweight constructions the range is exceeded twofold, which causes discomfort in the premises.
14) The mathematical model of buildings developed as part of the thesis proved that it is unnecessary for the heating systems of massive construction buildings to use the lowest temperature of 5 days, because when the temperature temporarily falls below -15 °C, the indoor temperature does not decline sharply; the same cannot be said about lightweight construction buildings – their indoor temperature, in accordance with experimental data, fluctuates along with the outdoor temperature.
15) A detailed model can be used for the processing of experimental data – as proven in this work, by using a simplified, approximated model, it is possible to obtain real values of weather conditions and indoor parameters.
16) The experimental measurements are dependent on the outdoor air parameters, which are variable and differ each year. Because of that, the obtained results may differ in other time periods, and therefore the final conclusions and results provide only general information, which may slightly vary from year to year.
17) Thermal stability is an important property of building constructions; if it is impossible in an emergency to quickly restore heat supply, the massive construction walls are able to maintain heat in the building for 8 h or 33% longer that a lightweight construction building.
18) The heating variation coefficient widely used in practice until now for buildings with district heating was 0.1. As part of the work, with the help of finite element computational dynamics software, it was proven that the coefficient varies both at different temperatures and depending on whether the external walls are lightweight or massive. Based on practical measurements and the developed mathematical model of the building, it was proven that the heating variation coefficient ranges from 0.1 to 0.36 for massive constructions and from 0.05 to 0.3 for lightweight building enclosures.
19) Based on the results of the work, proposals were developed for improvement of the regulatory documents:
    - Establish minimum values not only for heat transfer, but also for specific heat capacity or the material's ability to absorb thermal energy, which would improve thermal inertia in heated buildings;

- Include in LBN 231 “Heating and ventilation of buildings” a design temperature of -15 °C for massive constructions and -19 °C for lightweight constructions, because the currently used heating system design temperature is irrationally high, and the same temperature should not be applied to massive and lightweight building enclosures.
- Supplement LBN 231 “Heating and ventilation of buildings” with tabular values to determine the inertia coefficient for massive constructions $D \geq 6$ and for lightweight construction buildings $D \leq 5$.
- Supplement LBN 231 “Heating and ventilation of buildings” with recommendations for ensuring air exchange in high-rise apartment buildings.
- Introduce in LBN 231 “Heating and ventilation of buildings” the heating variation coefficient m.
- Establish in LBN 002-1 “Thermal Engineering of Building Envelopes” the minimum air permeability requirements for air ducts in buildings.

20) Massive building constructions require a significantly larger initial capital investment, however, by conducting an analysis of financial efficiency, it was proven that the recoupment period for such buildings is 32 years, but, taking into consideration the time of use of the building, it pays off threefold, and in terms of building stability and comfort, massive constructions are a better choice than lightweight construction buildings.

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