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Contribution to the Research and Development of Innovative Building Components with Embedded Energy-Active Elements

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Abstract: The research described in this study focuses on the innovation and optimization of building envelope panels with integrated energy-active elements in the thermal barrier function. It is closely related to developing and implementing the prototype prefabricated house IDA I with combined building-energy systems using renewable energy sources. We were inspired by the patented ®ISOMAX panel and system, which we have been researching and innovating for a long time. The thermal barrier has the function of eliminating heat loss/gain through the building envelope. By controlling the heat/cold transfer in the thermal barrier, it is possible to eliminate the thickness of the thermal insulation of the building envelope and thus achieve an equivalent thermal resistance of the building structure that is equal to the standard required value. The technical solution of the ISOMAX panel also brings, besides the use of the thermal barrier function, the function of heat/cold accumulation in the load-bearing part of the building envelope. Our research aimed to design and develop a panel for which the construction would be optimal in terms of thermal barrier operation and heat/cold accumulation. As the production panels in the lost formwork of expanded polystyrene (according to the patented system) proved to be too complicated and time consuming, and often showed shortcomings from a structural point of view, the next goal was to design a new, statically reliable panel construction with integrated energy-active elements and a time-saving, cost-effective, unified production directly in the panel factory. In order to develop and design an innovative panel with integrated energy-active elements, we analyzed the composition of the original panel and designed the composition of the innovative panel. We created mathematical–physical models of both panels and analyzed their energy potential. By induction and an analog form of formation, we designed the innovative panel. Based on the synthesis of the knowledge obtained from the scientific analysis and the transformation of this data, most of the building components and all the panels with integrated energy-active elements were manufactured directly in the prefabrication plant. Subsequently, the prototype of the prefabricated house IDA I was realized. The novelty of our innovative building envelope panel solution lies in the panel's design, which has a heat loss/gain that is 2.6 times lower compared to the ISOMAX panel.

Keywords: active energy elements (EAE); active thermal protection (ATP); thermal barrier (TB); renewable energy sources (RES); heat/cold accumulation

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1. Introduction

Energy self-sufficiency and security are among the priorities of all governments. Scientists worldwide are looking for solutions to halt climate change on our planet and reduce dependence on fossil fuels. Our research focuses on innovating and optimizing energy systems that use renewable energy and waste heat from technologies. Building structures that have an internal energy source with active thermal protection (ATP) represent technical solutions with a high potential to use environmentally friendly energy sources.

Active thermal protection is a dynamic process that is characterized by the building of structures with integrated active elements which are themselves characterized by one or more functions in different modes of energy systems operations. The energy functions of ATP are: thermal barrier, large-scale radiant low-temperature heating/high-temperature cooling, heat/cool storage, solar and ambient energy capture, and heat/cool heat recovery.

The research described in this study focuses on the innovation and optimization of building envelope panels with integrated energy-active elements in the thermal barrier function. The field of combined building-energy systems has been researched in our department for a long time, since approximately 2004. The contribution to the research and development of innovative building components with embedded energy-active elements is closely related to developing and implementing the prototype prefabricated house, IDA I (the name of the prototype prefabricated house was derived from the first name of the wife of the client of the development and implementation of the building, Ida, in accordance with the work contract), with combined building-energy systems using renewable energy sources (RES)(Figure 1).

Figure 1. A view of the construction of the prototype prefabricated house IDA I [1].

We were inspired by the patented ®ISOMAX panel and system, [2], which we have been researching and innovating for a long time. The thermal barrier has the function of eliminating heat loss/gain through the building envelope. By controlling the heat/cold transfer in the thermal barrier, it is possible to eliminate the thickness of the thermal insulation of the building envelope and thus achieve an equivalent thermal resistance for the building structure that is equal to the standard required value.

Based on a request from the practice, we were approached by AQUA IDA Slovakia, s. r. o. in 2005. (Currently Paneláreň Vrakuňa, a. s.)—the owner of the license of the building technology with the name and trademark ®ISOMAX [2]—to develop a prototype prefabricated house called IDA I. In accordance with the work contract HZ 04-309-05 between the customer and the Department of Building Services of the Faculty of Civil Engineering of the STU in Bratislava, a prototype of the panel house IDA I was developed, designed, and implemented in 2005–2006. It currently serves as an administrative building for the joint-stock company Paneláreň Vrakuňa (responsible researcher: Kalús, D.) [1].

The technical solution of the ISOMAX panel also brings, besides the use of the thermal barrier function, the function of heat/cold accumulation in the load-bearing part of the building envelope. Our research aimed to design and develop a panel for which the construction would be optimal in terms of thermal barrier operation and heat/cold accumulation. The novelty of our innovative building envelope panel solution lies in the panel's design, which has a 2.6 times lower heat loss/gain compared to the ISOMAX panel from the load-bearing part of the panels, which accumulates heat/cool for controlled operation of the thermal barrier. So, in addition to a higher equivalent thermal resistance compared to the ISOMAX panel, our innovative building envelope panel has significantly lower requirements for the operation of the circulation pumps. This result lowers the building's energy intensity and is both economically efficient and environmentally friendly.

The production panels in lost formwork of expanded polystyrene, according to the patented system, proved too complicated and time-consuming (Figure 2). Because the panels often showed shortcomings from a structural point of view, the next goal was to design a new, statically reliable panel construction method that had integrated energy-active elements and a timesaving, cost-effective, unified production directly in the panel factory. The sponsor's priority for the applied research was that as many of the components of the IDA I prototype prefabricated house as possible should be mass-produced in prefabrication.

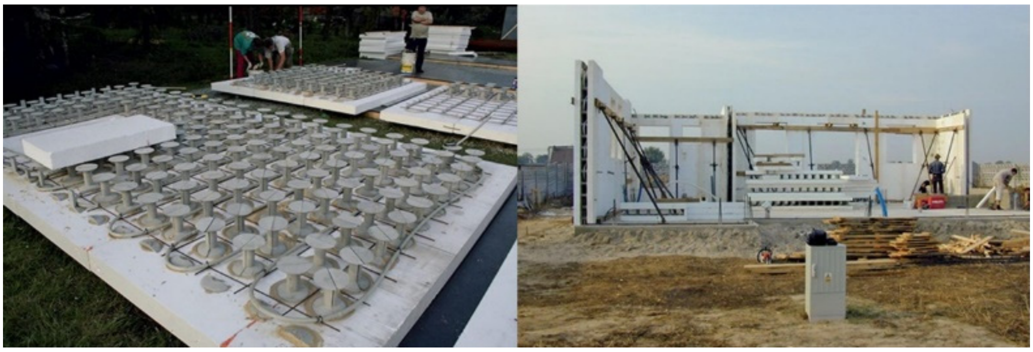


Figure 2. View of ISOMAX panel production from lost formwork [2].

In this study, we used the following methods of scientific work:

(1) Analysis and synthesis of knowledge in the field of active thermal protection and thermal barrier (Section 2);
(2) Description of the basic calculation equations for thermal barrier sizing (Section 3.1);
(3) Analysis of the ISOMAX panel composition and the development of a mathematical–physical model (Section 3.2);
(4) Analysis of the composition of the innovative envelope panel solution and development of the mathematical–physical model, (Section 3.3);
(5) Development and design of innovative panels and the details of panel joining (Section 3.4);
(6) Inductive and analog forms of formation of the innovative panel with integrated energy-active elements (Section 4.1);
(7) Analysis of the energy potential of the retrofitted panel with a thermal barrier compared to the original panel (Section 4.2);
(8) Synthesis of the knowledge obtained from the scientific analysis and the transformation of the data into the design and implementation of the IDA I prefabricated house prototype (Section 4.3).

Finally, we defined the objectives of our further research in Section 5.

2. Overview of Studies Dealing with Active Thermal Protection and Thermal Barrier

Lehmann et al., (2007) [3]: The authors examined the possibilities of use and functionality of thermally activated building systems (TABS). For the analysis of thermal comfort factors, maximum permissible thermal gains in the room, and cooling of the building mass for a typical administrative building, the building simulation program TRNSYS was used, in which the RC modeling approach for TABS was gradually developed. Based on the results, it can be concluded that, depending on the maximum permissible daily amplitude of the room temperature, it is possible to use the modules to control typical heat gain profiles with a peak load of up to approx. 50 W/m^2 of floor area. However, the design of the panels will, in most cases, be decisive for transitional periods with already high solar gains and a still-limited comfort range, thus limiting the maximum load to lower values. The results also showed that room-side processes are hardly affected by supply-side processes. In the case of cooling, this makes it possible to extend the re-cooling period of the fabric to 24 h a day with correspondingly “high” supply temperatures and a reduction in the maximum load by up to 50%. The stated results can indicate whether the slats can be used in a specific building and provide relevant parameters for dimensioning the slats.

Gwerder et al., (2008) [4]: The article outlined the basic thermal models, assumptions, and gives a procedure and example of the application of the calculation method for TABS. The integration of the building structure as TABS for energy storage has been shown to be energy efficient and economically viable for cooling and heating buildings. However, control remained an issue that needed to be improved. This paper outlined a method to enable both sizing and automated control of TABS with automatic switching between cooling/heating modes for variable comfort criteria.

Rijksen et al., (2010) [5]: The study aimed to establish general guidelines for the required cooling performance of an office building using TABS. On-site measurements aimed at obtaining the required cooling performance of the entire building as well as individual zones were carried out. In addition, indoor room environmental parameters and TABS surface temperatures were measured. The measured data were used to analyze the predictive performance of the simulation model. To obtain general guidelines for the required cooling performance of a standard office building, whole building simulations were used to determine the impact of different window sizes as well as variable internal heat gains. The required cooling performance was compared with the cooling performance of a system without energy balancing (e.g., cooled ceiling panels). Research has shown that TABS can reduce the cooling performance of a radiator by up to 50%. The results presented in this paper can be used for guidance in the first phase of the design process. The results focused on temperate climates and were derived for the climatic conditions in the Netherlands.

Kowalczuk and Krzaczek (2010) [6]: The authors focused on analyzing the thermal performance and stability of the thermal barrier (TB). The research was carried out on a 3D FE model (three-dimensional finite-element model) of a prefabricated outer wall component that had a built-in TB formed by a polypropylene U-pipe system with a flowing liquid. The temperature of the TB was fixed at 17 °C, although it varied only to a small extent during the year. The FE analysis was supported by a new SVC (scheduling variable controller) control system implemented in FORTRAN to simulate real working conditions. The FE simulations showed that the optimal mass flow range is 0.05–1.0 kg/s. No significant influence of TB placement on the thermal behavior of the external prefabricated component was found. The optimal design of the outer wall with a TB is a multilayer structure composed of at least three layers: an outer insulating layer, a massive core layer with the TB U-pipe system, and an inner layer material of low thermal conductivity. The TB reduces the heating and cooling requirements by at least three times compared to a traditional exterior wall without a TB. The TB temperature, almost fixed at 17 °C, radically reduces the risk of water vapor condensation. It allows for designing insulation layers on the inside of the exterior walls. The TB technique can thus be successfully implemented both in designing new buildings and in the thermal modernization of existing buildings.

Lehmann et al., (2011) [7]: The authors investigated the influence of a control strategy, a hydronic circuit, and a (cold) generation system on the energy efficiency of TABS. Based on a case simulation study for a typical Central European office building, they found that TABS with separate zoned return water systems can achieve energy savings of around 20–30% of heating and cooling demand compared to conventional zoned return water. With the intermittent pulse width modulation (PWM) system control strategy, it is possible to reduce the electrical energy consumption of circulating water pumps by more than 50% compared to continuous operation. In terms of cooling generation for TABS, free cooling with a wet cooling tower has been shown to be most effective when the cooling source is outside air. Variants with mechanical chillers show 30–50% higher electrical energy requirements for the production and distribution of cold, even though their running times are much shorter than the cooling towers' operating times.

Stojanovic et al., (2014) [8]: The study focused on the possibilities of increasing the energy efficiency of buildings when using integrated thermally activated systems that use geothermal energy. It analyzed the effect of temperature, as well as the type and thickness of other materials of the nontransparent part of the building façade, on energy efficiency, as this type of element strongly depends on these parameters. The building energy demand for heating was obtained for a real apartment building in Serbia using EnergyPlus software. The building with all the necessary inputs for the simulation was modeled in Google SketchUp using the Open Studio Plug-in. The obtained results were compared with the measured energy consumption for heating. The results showed that thermally activated building systems are a good way to increase the energy efficiency of a building and that, by applying certain temperatures within this element, a low-energy house standard can be achieved.

Babiak et al., (2015) [9]: A study compared TABS with traditional convection air conditioning and fan coil systems in office buildings in France, Lyon. TABS is a combined heating and cooling system with piping embedded in structural concrete slabs or walls of multistory buildings. An evaluation project had been performed by appointing a building energy simulation consultant. The thermal indoor climate and energy modeling were conducted, and heating/cooling load profiles were provided for selected systems. The HVAC (heating, ventilation, and air conditioning) schemes were selected based on what was commonly specified in France for similar projects. Based on the thermal modeling results, the consultant created schemes for each method of mechanical service. The cost amount was obtained from various sources. A life cycle cost analysis provides an assessment of different methods of heating, cooling, and ventilation. The cost data and building energy simulations showed that TABS reduces the total cost of the building by a significant 16–27% compared to other air handling equipment. The results also showed that selecting TABS for the HVAC scheme will improve the indoor thermal energy environment (class B PMV index ranges from 22% to 24% more working hours in the two selected rooms). In conclusion, TABS has proven to be adaptable and cost-effective for French conditions.

Yu et al., (2016) [10]: The authors proposed a novel idea of using an MTC (minitubular capillary network) with low-grade thermal water for the thermal activation of conventional walls. In contrast to the general indoor water embedded design, this innovation applies MTC at the boundary between the space and the outdoor environment and brings the thermal energy closer to the load. It can significantly relax the constraints on water temperature and facilitate the direct use of low-grade renewable energy in buildings without conversion. To investigate the thermodynamic performance of the wall, a transient dynamic model was developed for the cases with and without the MTC thermal layer. Simulated results showed that the embedded MTC wall could significantly change the thermodynamics of the wall, from balancing environmental influences to indirectly cooling the space. This wall can activate the wall, can effectively stabilize the internal surface temperature, compensate for heat gains, and supply cooling energy to the space in summer.

Kisilewicz et al., (2019) [11]: In the paper, the authors discussed how an active insulation system can replace commonly used standard passive insulation systems. The research was carried out in an experimental apartment building in the city of Nyiregyház in Hungary, which was equipped with an innovative system that had a direct connection from the ground heat exchanger to the wall heat exchanger. The results were obtained using the method of experimental measurements of selected physical quantities and dynamic simulation. Initial research results concluded that active thermal insulation significantly improves the insulation parameters of the outer wall. In the analyzed periods, the total amount of heat loss through the perimeter walls decreased from 53% in February to 81% in November. The equivalent thermal transmittance U_{eq} of the analyzed wall was dependent on the local climatic conditions and was 0.047 W/(m^2·K) in November and 0.11 W/(m^2·K) in March, while the standard heat transfer value was 0.282 W/(m^2·K). These research results should be the basis for implementing an innovative system in buildings with almost zero energy consumption.

Figiel and Leciej-Pirczewska (2020) [12]: the authors studied the effect of an active thermal barrier on heat loss and CO_2 emissions. The analysis was performed for a family house in a temperate climate based on parameters taken from one of the Polish meteorological databases. The calculations were carried out using current procedures for assessing the energy efficiency of the building. General calculations of energy demand for heating, cooling, and ventilation were based on methods from CEN standards. Research has shown that the application of a thermal barrier has the effect of reducing heat loss from the inside. Placing the barrier close to the exterior is beneficial and installing it during a thermal renovation can provide significant energy improvements and be more environmentally friendly.

Kalús et al., (2021) [13]: The article focused on describing an innovative solution and application of active thermal protection (ATP) of buildings using thermal insulation panels, with the active regulation of heat transfer in the form of a contact insulation system. Thermal insulation panels are part of a prefabricated light outer shell, which, together with a system of low-temperature heating and high-temperature cooling, creates an internal environment. The energy source is usually renewable energy sources or technological waste heat. Research and development of an innovative facade system with ATP is in the phase of computer simulations and laboratory preparation for measuring thermal insulation panels' parameters with different energy function combinations. The paper presented the theoretical assumptions, calculation procedure, and parametric study of three basic design solutions of combined energy wall systems in the function of low-temperature radiant heating and high-temperature radiant cooling. The most significant limitation of implementing this technology in practice is that thermal insulation panels with ATP are not yet certified and produced by any manufacturer. We recommend further research, especially towards multifunctional thermal insulation panels with ATP in low-temperature radiant heating/high-temperature radiant cooling modes, but also as a solar energy absorber and ambient energy in cooperation with heat pumps.

Kalús et al., (2021) [14]: The study aimed to evaluate TBs in terms of energy demand, economic efficiency, and environmental friendliness by comparing the use of a classic perimeter wall with the required thickness of thermal insulation (that meets the normative requirements for thermal resistance) and a perimeter wall with an integrated TB (significantly eliminating the thermal insulation thickness). The use of a thermal barrier was evaluated using a number of economic indicators. Economic indicator one compared the cost of heat delivered to the TB in a building with significantly eliminated insulation with the saved cost of insulation at standard thickness. Economic indicator two compared the cost of heat delivered to the TB in a building with significantly eliminated thermal insulation with the potential gain from the sale of the usable area of the building gained relative to the area with the normative thickness of thermal insulation. Economic indicator three compared the cost of heat delivered to the TB in a building with significantly eliminated insulation with the cost of grey energy at the normative insulation thickness. On the basis of a parametric study based on theoretical assumptions, it can be concluded that the thermal barrier represents a very promising and effective solution in terms of evaluating economic indicators one to three, which are even more significant if heat from renewable energy sources (RES) or waste heat is used for TB.

Research in the field of active thermal protection and thermally activated building systems in connection with renewable energy sources have been carried out by many other scientists and their colleagues, including as Maruyama et al., (1989) [15], Olesen et al., (2006) [16], Krecké et al., (2007) [17], Gwerder et al., (2009) [18], Xie et al., (2012) [19], Doležel (2014) [20], Ibrahim et al., (2021) [21], and Kalús et al., (2010) [22].

3. Innovated Thermal Barrier Panel Compared to the Patented ISOMAX Panel

In Section 3.1, we present the initial calculation relations for the sizing of the thermal barrier. In Section 3.2, we analyze the composition of the patented ISOMAX panel. We present the results of a parametric study of the temperatures in the different layers of the building structure and graphically illustrate the progression of temperatures from the interior to the exterior in winter and summer. We analyze the energy potential of the patented ISOMAX panel. In Section 3.3, we analyze the design of an innovative thermal barrier panel and also present the results of a parametric study of the temperatures in the different layers of the building structure and graphically illustrate the progression of temperatures from the interior to the exterior in winter and summer. We analyze the energy potential of the upgraded panel. In Section 3.4, we give the basic details of joining the panels.

3.1. Initial Calculation Relations for Thermal Barrier Dimensioning

The idea of using a thermal barrier to eliminate heat loss/heat gain throughout the building structure is based on the knowledge of the temperatures between the layers—specifically between the static load-bearing layer and thermal insulation layers of the building structure. When calculating the thermal resistance R ((m^2·K)/W) and the heat transfer coefficient U (W/(m^2·K)) of a multilayer building structure, the temperatures between the layers are calculated.

The thermal resistance of the jth structure is calculated by:

$$R_i = \frac{d_j}{\lambda_j}, \tag{1}$$

where:

R_i is the thermal resistance of the jth layer of the structure ((m^2·K)/W),
d_j is the thickness of the jth layer of the structure (m), and
λ_j is the coefficient of thermal conductivity of the jth layer of the structure (W/(m K)) [23].

The thermal resistance of a multilayer structure shall be calculated:

$$R_c = \sum R_i, \tag{2}$$

$$R = R_{si} + R_c + R_{se}, \tag{3}$$

where:

R_j is the thermal resistance of the jth layer of the structure ((m^2·K)/W),
R_c is the total thermal resistance of the structure ((m^2·K)/W),
R_{si} is the thermal resistance to heat transfer at the internal surface of the structure ((m^2·K)/W),
R_{se} is the thermal resistance to heat transfer at the external surface of the structure ((m^2·K)/W), and
R is the thermal resistance of the structure ((m^2·K)/W), [23].

The value of the heat transfer coefficient of a multilayer structure is calculated as follows:

$$U = \frac{1}{R_{si} + R + R_{se}}, \tag{4}$$

where:

U is the heat transfer coefficient of the structure ((m^2·K)/W),
R_{si} is the thermal resistance to heat transfer at the internal surface of the structure ((m^2·K)/W),
R is the thermal resistance of the structure ((m^2·K)/W), and
R_{se} is the thermal resistance to heat transfer at the external surface of the structure ((m^2·K)/W), [23].

The temperature in the jth layer of the structure is calculated:

$$\theta j = \theta i - U \times (\theta i - \theta_e) \times (R_{si} + \sum R_j), \tag{5}$$

where:

θj is the temperature in the jth layer of the structure (°C),
θi is the internal design temperature (°C),
θ_e is the outdoor design temperature in winter (°C),
U is the heat transfer coefficient of the structure ((m^2·K)/W),
R_{si} is the thermal resistance to heat transfer at the internal surface of the structure ((m^2·K)/W), and
$\sum R_j$ is the sum of thermal resistances of the jth layers of the structure ((m^2·K)/W) [23].

The external wall prefabricated component is assumed to be a 3D system (Figures 4 and 7). The heat transfer equation for transient conditions in a Cartesian coordinate system is as follows:

$$C_p \rho \frac{\partial T}{\partial t} = \lambda \left(\frac{\partial^2 T}{\partial x} + \frac{\partial^2 T}{\partial y} + \frac{\partial^2 T}{\partial z} \right), \quad (6)$$

where:

C_p is the specific heat under constant pressure (kJ/kg K),
p is the density of the wall layer material (kJ/m^3)],
T is the temperature (°C), and
t is the time (s) [24].

Suppose the outer wall at constant temperature T_i separates the inner zones from the ambient conditions—it is possible to define boundary conditions on the S_i and S_e surfaces using Newton's law. When using the convection/radiative heat transfer coefficient, it is possible to determine the inner S_i surface's convection and radiative heat transfer rates. Based on these facts, the boundary conditions after the modification of Equation (6) on the S_i surface are given as follows:

$$\lambda \left. \frac{\partial T(t)}{\partial x} \right|_{s_i} = h_i [T_{Fi}(t) - T_i] \quad (7)$$

where:

λ is the thermal conductivity (W/m K),
h_i is the convective/radiative heat transfer coefficient on the internal surface (W/m^2·K),
$T_{Fi}(t)$ is the internal surface temperature (°C), and
T_i is the internal air temperature (°C) [24].

For the heat exchange between the external surface S_e and the external environment, convection and radiation are considered separately. The convection heat transfer coefficient defines convection, and the solar temperature defines radiation. The actual heat transfer mechanism between the roof or wall surface and the outside air is replaced by a fictitious solar temperature T_e, which provides the same heat transfer rate. Considering variable ambient conditions, the boundary conditions at the external surface S_e can be defined as follows:

$$\lambda \left. \frac{\partial T}{\partial x} \right|_{s_e} = h_e(t) [T_e(t) - T_{Fe}(t)] \quad (8)$$

where:

$h_e(t)$ is the convective heat transfer coefficient on the external surface (W/m^2·K),
$T_e(t)$ is the solar temperature (°C), and
$T_{Fe}(t)$ is the external surface temperature (°C) [24].

The boundary conditions on the adiabatic surfaces S_{a1} and S_{a2} are defined as follows:

$$q(t) \mid S_{a1} = 0, \quad (9)$$

and

$$q(t) \mid S_{a2} = 0, \quad (10)$$

where:
q(t) is the heat flux normal to the surface (W/m^2), and
S_{a1} and S_{a2} are adiabatic surfaces (m^2) [24].

3.2. The Composition of the Patented ISOMAX Panel

Building envelope panels, according to the ISOMAX system [2], consist of a lost formwork on the interior and exterior side—slabs of expanded polystyrene with a thickness of 75 mm and a load-bearing static reinforced concrete part with a thickness of 150 mm, in which PP-20/2 tubes are embedded at an axial distance of 100 to 250 mm from each other, forming the circuits of the thermal barrier (Figure 3). The wall constructed in this way functions not only as a thermal barrier, but also accumulates heat and cold in the mass of the load-bearing part where a large-capacity reservoir is formed.

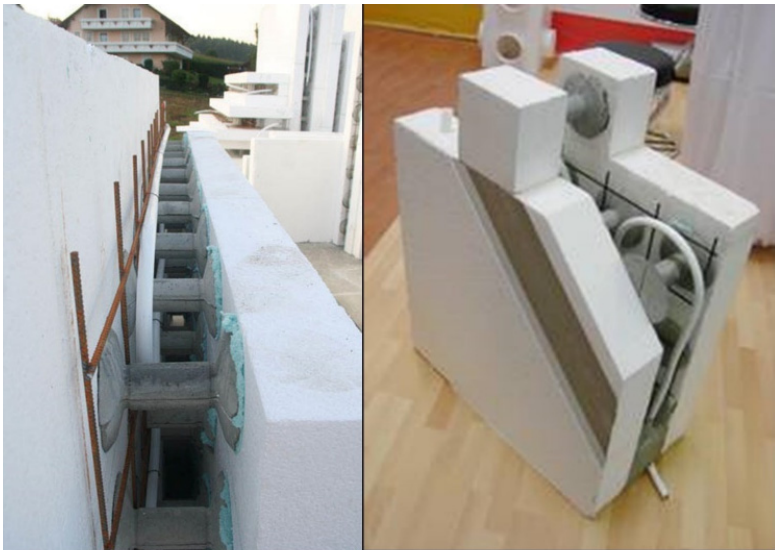
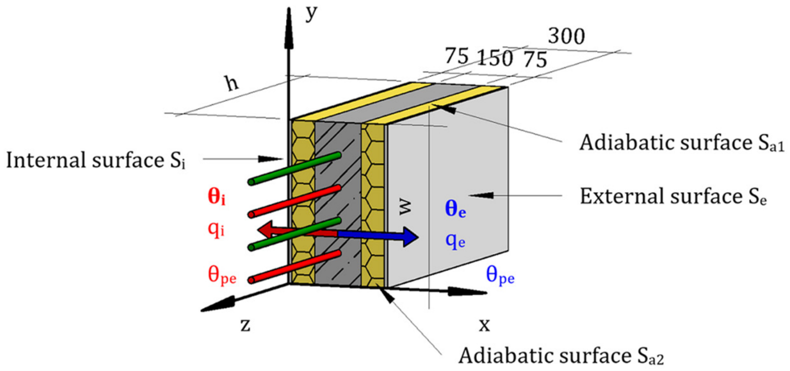


Figure 3. View of the lost formwork of the ISOMAX panel and the principal location of the thermal barrier [2].

In our research, in addition to troubleshooting the ISOMAX panels for on-site implementation, we also focused on the energy analysis of the thermal barrier function and the heat/cold accumulation potential in the mass of the load-bearing reinforced concrete wall. For the purpose of the parametric study, a mathematical–physical model of the wall ISOMAX was created (Figure 4). The basic physical properties of the building materials comprising the ISOMAX panel—thickness, bulk density, thermal conductivity coefficient, specific heat capacity, and diffusion resistance factor—are tabulated in the mathematical–physical models included in Figure 4.

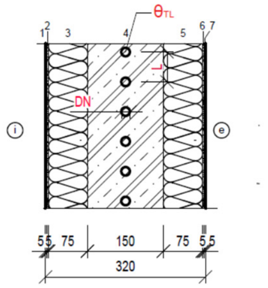
The function of the thermal barrier is to reduce heat loss/gain through the external building envelope. In terms of the calculation procedure described in Section 3.1, the thermal resistance of the building structure R ((m^2·K)/W), the thermal transmittance of the building structure U (W/(m^2·K)), the thermal transmittance of the thermal insulation on the exterior side U_{TIe} (W/(m^2·K)), and the temperature θ_{TB} (°C) in the thermal barrier layer for different thicknesses of the thermal insulation on the exterior side are determined. Table 1 shows the values for the heating period for an indoor temperature of θ_i = +20 °C and an outdoor design temperature of θ_e = −11 °C. Table 2 shows the values for the summer period for an indoor temperature of θ_i = +26 °C and an outdoor temperature of θ_e = +34 °C. Suppose the external thermal insulation thickness remains constant, and a heat transfer fluid is supplied to the thermal barrier to heat/cool the layer. In that case, the building structure has an equivalent thermal resistance $R_{equivalent}$ ((m^2·K)/W) corresponding to the temperature in the thermal barrier layer (see Tables 1 and 2).



Thermal technical properties and assessment of the perimeter wall fragment

Marginal conditions for interior:

θ_i = 20 °C
φ_i = 50%
R_{si} = 0.13 m²·K/W



Marginal conditions for exterior: (Bratislava)

θ_e = −11 °C
φ_e = 83%
R_{se} = 0.04 m²·K/W

Others considered conditions:

$\theta_{TL} = \theta_{TL}$ °C
DN = DN
L = L mm

Number	Name of the material	Thickness	Volumetic weight	Thermal conductivity coefficient	Specific heat capacity	Diffusion resistance factor	Thermal resistance	Diffuse resistance
	Symbol	d	ρ	λ	c	μ	R	Rd×10⁹
	Unit	m	kg/m³	W/(m.K)	J/(kg.K)	(-)	m².K/W	m/s
1	Interior plaster	0.005	2000	0.990	790	19.0	0.005	0.50
2	Reinforcing mortar	0.005	1300	0.800	1020	18.0	0.006	0.48
3	Thermal insulation EPS	0.075	40	0.037	1270	45.0	2.027	17.93
4	Reinforced concrete	0.150	2300	1.430	1020	29.0	0.105	23.11
5	Thermal insulation EPS	0.075	40	0.037	1270	45.0	2.027	17.93
6	Reinforcing mortar	0.005	1300	0.800	1020	18.0	0.006	0.48
7	Exterior plaster	0.005	2000	0.990	790	19.0	0.005	0.50

Results of the calculation of thermal technology parameters	
Thermal resistance of construction	R = 4.182 m².K/W
Diffuse resistance of construction	$R_d = 60.93 \times 10^9$ m/s
Heat transfer coefficient	U = 0.231 W/(m².K)

Assessment of fragment construction		Rating
Thermal resistance	R = 4.182 m².K/W < R_{r1} = 6.50 m².K/W - recommended value	does not meets
Heat transfer coefficient	U = 0.231 W/(m².K) > U_{r1} = 0.15 W/(m².K) - recommended value	does not meets

θTL, DN, L - variable value

Figure 4. Mathematical–physical model: thermal properties and evaluation of the ISOMAX perimeter wall fragment. q_i—heat flow towards the interior (W/m^2), q_e—heat flow towards the exterior (W/m^2), θ_i—internal calculation temperature (°C), θ_e—outdoor calculation temperature (°C), θ_{pi}—interior surface temperature (°C), θ_{pe}—exterior surface temperature (°C), θ_{TL}—temperature of the heating medium (°C), φ_i—design relative humidity of the indoor air (%), φ_e—design relative humidity of the outdoor air (%), R_{se}—thermal resistance to heat transfer at the external surface of the structure ((m^2·K)/W), R_{si}—thermal resistance to heat transfer at the internal surface of the structure ((m^2·K)/W), *i*—interior, *e*—exterior, *DN*—pipe dimension, *L*—pipe pitch (mm), *h*—fragment length (m), *w*—height of the fragment (m).

Table 1. Results of calculation of physical variables during the heating season.

Heating by ISOMAX 75–150-d_2													
d_2 (mm)	**75**	**100**	**125**	**150**	**175**	**200**	**225**	**250**	**300**	**400**	**500**	**750**	**1000**
R (m^2·K/W)	4.182	4.857	5.533	6.209	6.884	7.560	8.236	8.911	10.263	12.965	15.668	22.425	29.182
U (W/(m^2·K))	0.231	0.199	0.175	0.157	0.142	0.129	0.119	0.110	0.096	0.076	0.063	0.044	0.034
U_{TI} (m^2·K/W))	0.481	0.363	0.292	0.244	0.209	0.183	0.163	0.147	0.123	0.092	0.074	0.049	0.037
θ_m (°C)	3.91	5.98	7.64	8.95	10.01	10.88	11.62	12.24	13.25	14.64	15.55	16.88	17.60

Table 2. Results of calculation of physical quantities during the cooling season.

Cooling by ISOMAX 75–150-d_2													
d_2 (mm)	**75**	**100**	**125**	**150**	**175**	**200**	**225**	**250**	**300**	**400**	**500**	**750**	**1000**
R (m^2·K/W)	4.182	4.857	5.533	6.209	6.884	7.560	8.236	8.911	10.263	12.965	15.668	22.425	29.182
U (W/(m^2·K))	0.231	0.199	0.175	0.157	0.142	0.129	0.119	0.110	0.096	0.076	0.063	0.044	0.034
U_{TI} (m^2·K/W))	0.481	0.363	0.292	0.244	0.209	0.183	0.163	0.147	0.123	0.092	0.074	0.049	0.037
θ_m (°C)	30.17	29.62	29.19	28.85	28.58	28.35	28.16	28.00	27.74	27.38	27.15	26.80	26.62

Figure 5 shows the temperature evolution in each layer of the ISOMAX panel during the heating and cooling seasons.

For the ISOMAX panel, the total thermal resistance R = 4.182 ((m^2·K)/W) and the heat transfer coefficient U = 0.231 (W/(m^2·K)). The heat transfer coefficient of the thermal insulation on the exterior side of the external wall is $U_{TI,e}$ = 0.481 (W/(m^2·K)). If we reach a temperature of +20 °C in the thermal barrier layer in winter, the specific heat loss from the thermal barrier to the exterior at a mean temperature of the heat transfer medium of +20 °C would be $q = 0.481 \times (20 - (-11)) = 14.911$ W/m^2. If a temperature of +26 °C is reached in the thermal barrier layer in summer, the specific heat gain to the thermal barrier from the exterior at a mean temperature of the heat transfer medium of +26 °C will be $q = 0.481 \times (26 - 34)) = -3.848$ W/m^2.

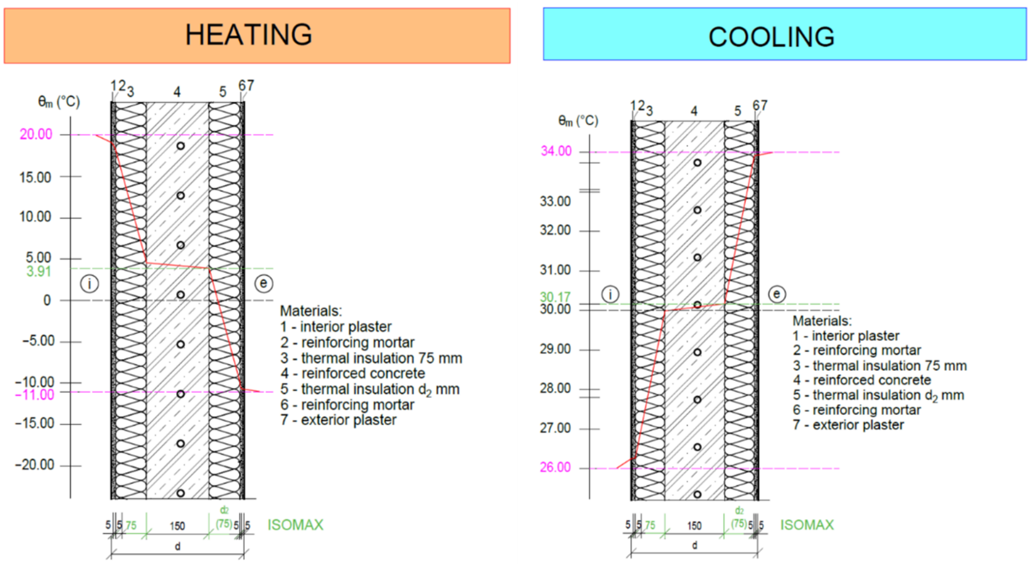


Figure 5. Temperatures in individual layers of the ISOMAX panel, i—interior, e—exterior.

3.3. Analysis of the Design of an Innovative Panel with a Thermal Barrier

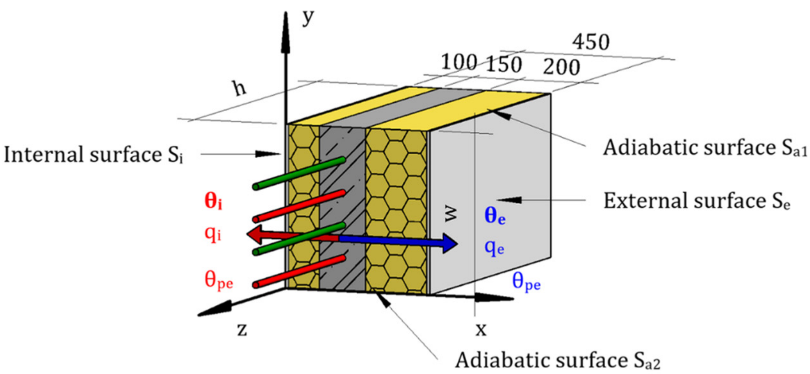
The design of the innovative panel with a thermal barrier was part of the overall upgraded solution of the ISOMAX system, which resulted in the design and realization of the prototype prefabricated house IDA I (Figure 6). The perimeter panels were designed with thermal insulation made of expanded polystyrene on the interior side with a thickness of 100 mm, and on the exterior side with a thickness of 200 mm, based on the energy analysis and the requirements for reducing the energy demand for heating. The supporting static reinforced concrete part of the panels, in which PP-20/2 tubes were embedded at an axial distance of 100 to 250 mm from each other, forming the thermal barrier circuits, was left at 150 mm thickness. Figure 7 shows a mathematical–physical model of an innovative thermal barrier perimeter panel solution.

Figure 6. Prototype of prefabricated house IDA I—view of the innovative panels with built-in thermal barrier and construction of the first floor [1].

By analogy with the ISOMAX panel, according to the calculation procedure described in Section 3.1, the thermal resistance of the building structure R ((m^2·K)/W), the heat transfer coefficient of the building structure U (W/(m^2·K)), the heat transfer coefficient of the thermal insulation on the outside U_{TIe} (W/(m^2·K)), and the temperature θ_{TB} (°C) in the thermal insulation layer were determined for the upgraded panel for different thicknesses of the thermal insulation on the outside. Table 3 shows the values for the heating period for an indoor temperature of θ_i = +20 °C and an outdoor design temperature of θ_e = −11 °C. Table 4 shows the values for the summer period for an indoor temperature of θ_i = +26 °C and an outdoor temperature of θ_e = +34 °C. If the thickness of the external thermal insulation remains constant and a heat transfer fluid is supplied to the thermal barrier to heat/cool the layer, the building structure has an equivalent thermal resistance $R_{equivalent}$ ((m^2·K)/W) corresponding to the temperature in the thermal barrier layer (see Tables 3 and 4).

The basic physical properties of the building materials comprising the innovative panel—thickness, bulk density, thermal conductivity coefficient, specific heat capacity, and diffusion resistance factor—are tabulated in the mathematical–physical models included in Figure 7.

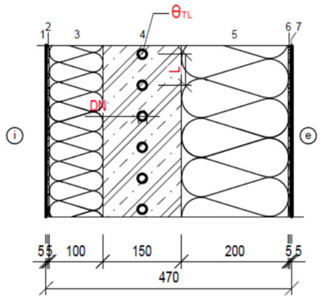
For the upgraded panel, the total thermal resistance R = 8.236 ((m^2·K)/W) and the heat transfer coefficient U = 0.119 (W/(m^2·K)). The heat transfer coefficient of the thermal insulation on the exterior side of the external wall is $U_{TI,e}$ = 0.183 (W/(m^2·K)). If we reach a temperature of +20 °C in the thermal barrier layer in winter, the specific heat loss from the thermal barrier to the exterior at a mean temperature of the heat transfer medium of +20 °C would be q = 0.183 × (20 − (−11)) = 5.673 W/m^2. If a temperature of +26 °C is reached in the thermal barrier layer in summer, the specific heat gain to the thermal barrier from the exterior at a mean temperature of the heat transfer medium of +26 °C will be q = 0.183 × (26 − 34)) = −1.464 W/m^2. Figure 8 shows the temperature evolution in the different layers of the upgraded panel during the heating and cooling season.



Thermal technical properties and assessment of the perimeter wall fragment

Marginal conditions for interior:

θ_i = 20 °C
φ_i = 50%
R_{si} = 0.13 m²·K/W



Marginal conditions for exterior: (Bratislava)

θ_e = −11 °C
φ_e = 83%
R_{se} = 0.04 m²·K/W

Others considered conditions:

θ_{TL} = θ_{TL}°C
DN = DN
L = L mm

Number	Name of the material	Thickness	Volumetic weight	Thermal conductivity coefficient	Specific heat capacity	Diffusion resistance factor	Thermal resistance	Diffuse resistance
	Symbol	d	ρ	λ	c	μ	R	Rd×10⁹
	Unit	m	kg/m³	W/(m.K)	J/(kg.K)	(-)	m².K/W	m/s
1	Interior plaster	0.005	2000	0.990	790	19.0	0.005	0.50
2	Reinforcing mortar	0.005	1300	0.800	1020	18.0	0.006	0.48
3	Thermal insulation EPS	0.100	40	0.037	1270	45.0	2.703	23.90
4	Reinforced concrete	0.150	2300	1.430	1020	29.0	0.105	23.11
5	Thermal insulation EPS	0.200	40	0.037	1270	45.0	5.405	47.81
6	Reinforcing mortar	0.005	1300	0.800	1020	18.0	0.006	0.48
7	Exterior plaster	0.005	2000	0.990	790	19.0	0.005	0.50

Results of the calculation of thermal technology parameters	
Thermal resistance of construction	R = 8.236 m².K/W
Diffuse resistance of construction	R_d = 96.78×10⁹ m/s
Heat transfer coefficient	U = 0.119 W/(m².K)

	Assessment of fragment construction	Rating
Thermal resistance	R = 8.236 m².K/W > R_{r1} = 6.50 m².K/W - recommended value	meets
Heat transfer coefficient	U = 0.119 W/(m².K) < U_{r1} = 0.15 W/(m².K) - recommended value	meets

θTL, DN, L - variable value

Figure 7. Mathematical–physical model: composition of an upgraded thermal insulation envelope panel. q_i—heat flow towards the interior (W/m^2), q_e—heat flow towards the exterior (W/m^2), θ_i—internal calculation temperature (°C), θ_e—outdoor calculation temperature (°C), θ_{pi}—interior surface temperature (°C), θ_{pe}—exterior surface temperature (°C), θ_{TL}—temperature of the heating medium (°C), φ_i—design relative humidity of the indoor air (%), φ_e—design relative humidity of the outdoor air (%), R_{se}—thermal resistance to heat transfer at the external surface of the structure ((m^2·K)/W), R_{si}—thermal resistance to heat transfer at the internal surface of the structure ((m^2·K)/W), *i*—interior, *e*—exterior, *DN*—pipe dimension, *L*—pipe pitch (mm), *h*—fragment length (m), *w*—height of the fragment (m).

Table 3. Results of calculation of physical variables during the heating season.

Heating by Innovated Construction 100–150-d_2													
d_2 (mm)	**75**	**100**	**125**	**150**	**175**	**200**	**225**	**250**	**300**	**400**	**500**	**750**	**1000**
R (m^2·K/W)	4.857	5.533	6.209	6.884	7.560	8.236	8.911	9.587	10.938	13.641	16.344	23.100	29.857
U (W/(m^2·K))	0.199	0.175	0.157	0.142	0.129	0.119	0.110	0.102	0.090	0.072	0.061	0.043	0.033
U_{TI} (m^2·K/W))	0.481	0.363	0.292	0.244	0.209	0.183	0.163	0.147	0.123	0.092	0.074	0.049	0.037
θ_m (°C)	1.82	3.97	5.67	7.04	8.17	9.05	9.93	10.63	11.77	13.38	14.46	16.07	16.96

Table 4. Results of calculation of physical variables during the cooling season.

Cooling by Innovated Construction 100–150-d_2													
d_2 (mm)	**75**	**100**	**125**	**150**	**175**	**200**	**225**	**250**	**300**	**400**	**500**	**750**	**1000**
R (m^2·K/W)	4.857	5.533	6.209	6.884	7.560	8.236	8.911	9.587	10.938	13.641	16.344	23.100	29.857
U (W/(m^2·K))	0.199	0.175	0.157	0.142	0.129	0.119	0.110	0.102	0.090	0.072	0.061	0.043	0.033
U_{TI} (m^2·K/W))	0.481	0.363	0.292	0.244	0.209	0.183	0.163	0.147	0.123	0.092	0.074	0.049	0.037
θ_m (°C)	30.69	30.14	29.7	29.34	29.05	28.8	28.6	28.42	28.12	27.71	27.43	27.01	26.79

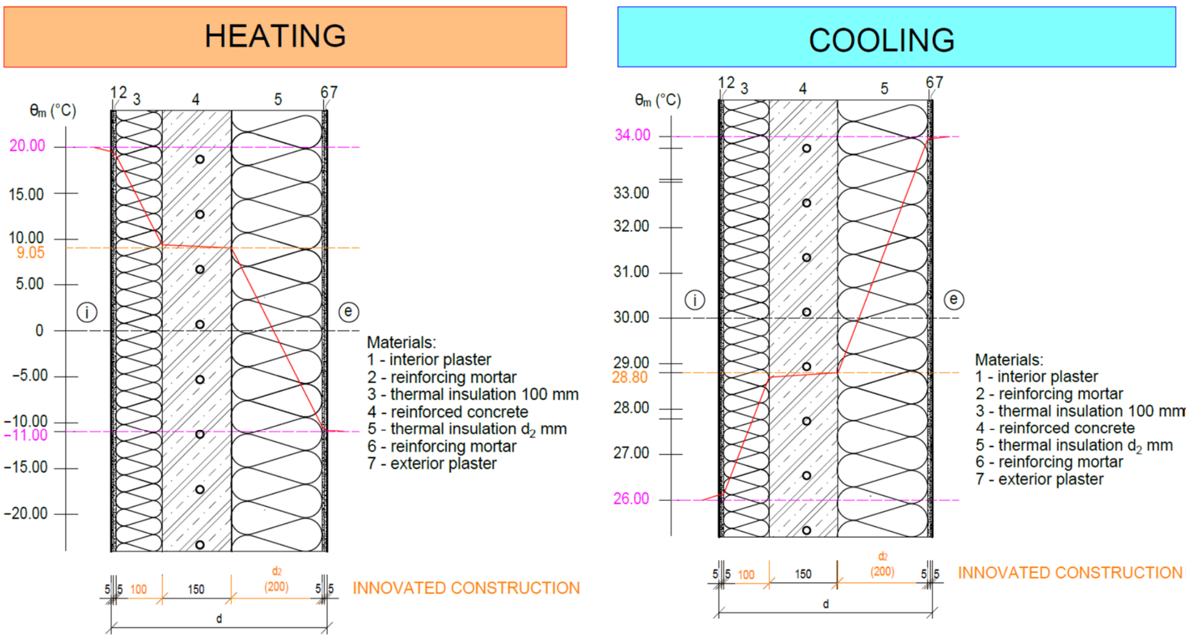


Figure 8. Temperatures in individual layers of the upgraded panel, i—interior, e—exterior.

This means that the construction of the perimeter panel that was designed by us shows approximately a 2.6 times lower specific heat loss from the thermal barrier to the exterior at a mean temperature of the heat transfer medium of 20 °C than the wall of the ISOMAX system [2].

3.4. Details on Connecting Panels during Construction

Our research was not focused on the static and technological design of the panel joints; therefore, we only presented the principal details of the panel joints (Figures 9 and 10). There are several variants for joining reinforced concrete panels. In designing the IDA I prototype panel house, the structural engineer and the panel plant technologist designed the standard joints at that time.

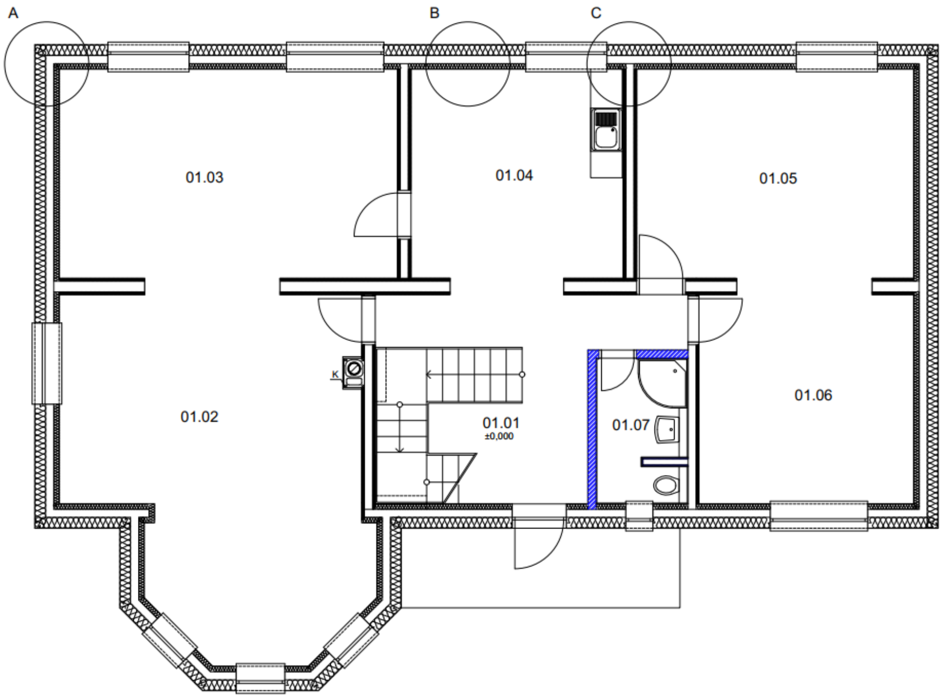


Figure 9. First floor plan showing the location of details A, B, and C; K—chimney for fireplace; the digit +0.000 indicates the ground floor elevation.

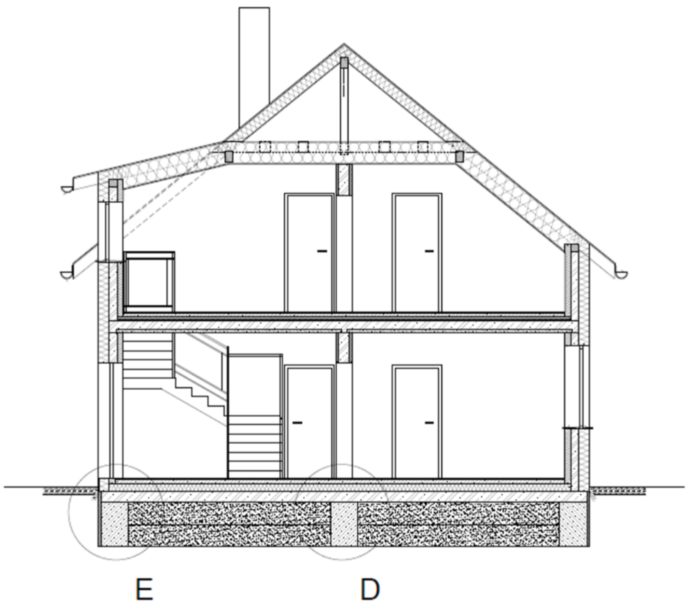


Figure 10. Cross section showing the location of details D and E.

Detail A (Figure 11) shows the corner joint of two perimeter panels. Detail B (Figure 12) shows the through joint of two perimeter panels. Detail C (Figure 13) shows a continuous joint of two perimeter panels with an internal load-bearing panel. Detail D (Figure 14) shows the connection of the inner load-bearing panel to the base plate. Detail E (Figure 15) shows the joint of the perimeter panel with the base plate.

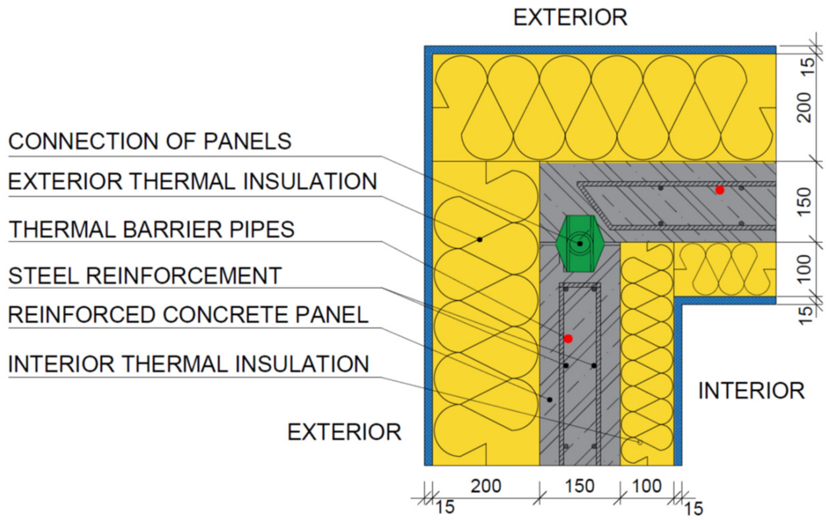


Figure 11. "Detail A", the corner joint of two perimeter panels. The colored points (red) in the picture are thermal barrier pipes.

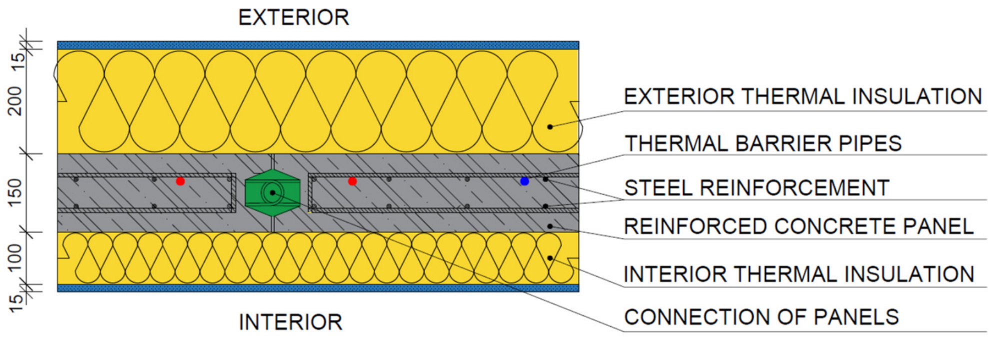


Figure 12. "Detail B", the through joint of two perimeter panels. The colored points (red and blue) in the picture are thermal barrier pipes.

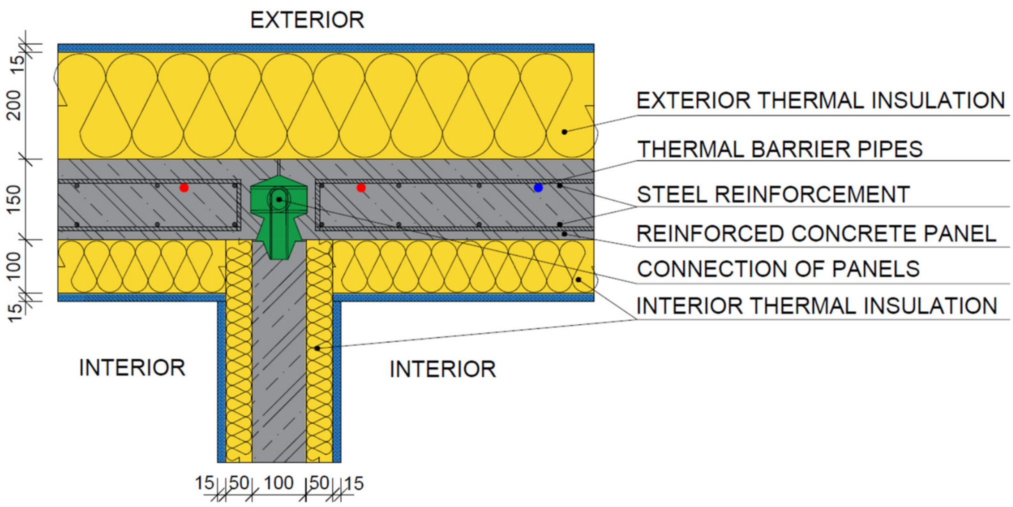


Figure 13. "Detail C", a through joint of two perimeter panels with an internal load-bearing panel. The colored points (red and blue) in the picture are thermal barrier pipes.

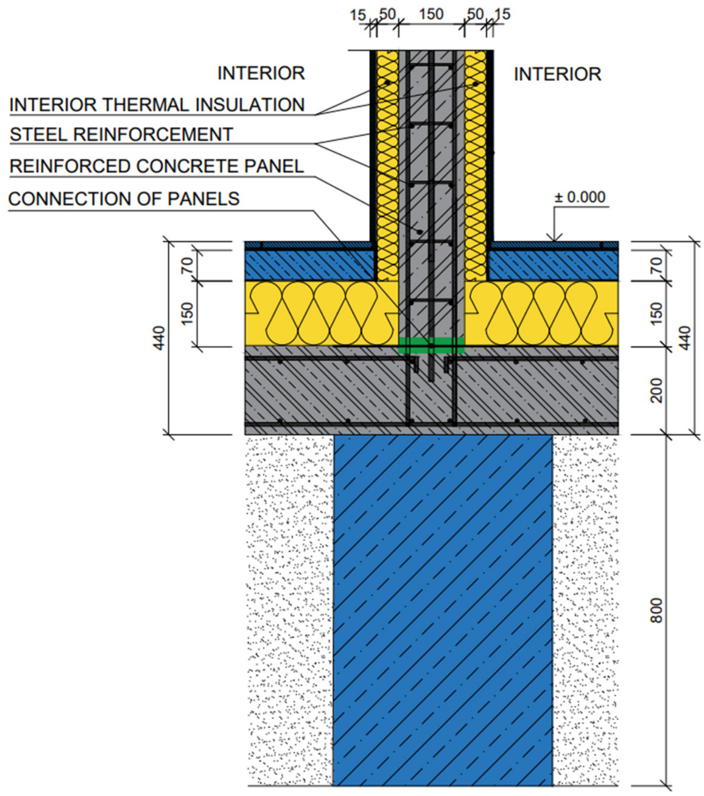


Figure 14. "Detail D", the connection of the inner load-bearing panel to the base plate.

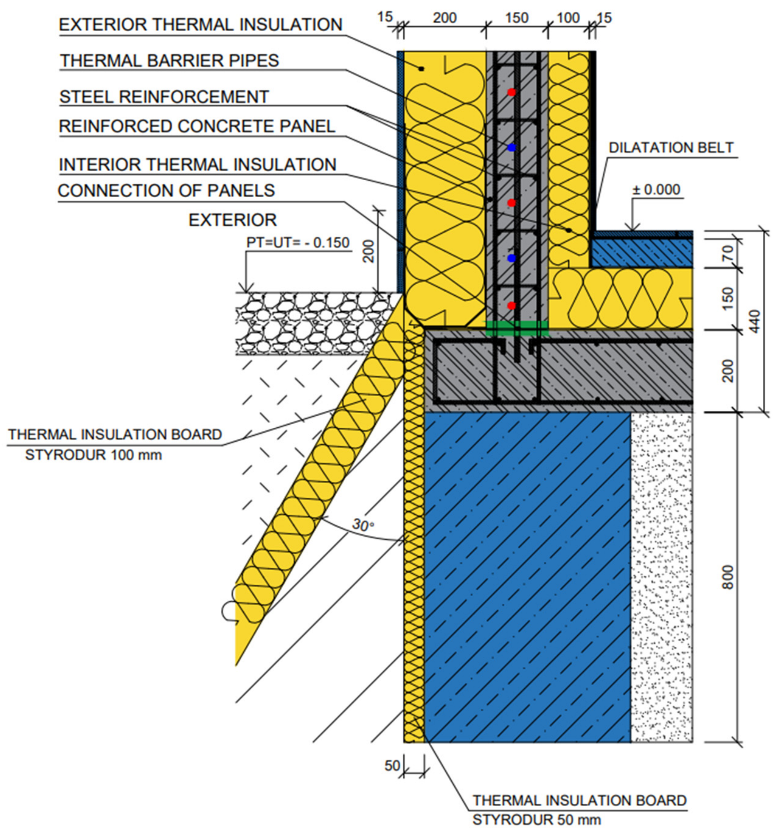


Figure 15. "Detail E", the joint of the perimeter panel with the base plate. The colored points (red and blue) in the picture are thermal barrier pipes.

4. Results and Discussion

In this section, we describe and analyze the most important results of our research:

- Induction and analog form of forming an innovative panel with integrated energy-active elements.
- Analysis of the energy potential of the retrofitted panel with a thermal barrier compared to the original panel.
- Synthesis of the knowledge obtained from the scientific analysis and transformation of the data into the design and implementation of the IDA I prefabricated house prototype.

4.1. Inductive and Analogous Form of the Formation of the Innovative Panel with Integrated Energy-Active Elements

As can be seen from the photos in Figures 2, 3, 16 and 17, the production of ISOMAX panels is quite laborious, lengthy, and, on the construction site, requires gradual implementation—pouring concrete. It is problematic to achieve uniform placement of the tubes in the center of the load-bearing reinforced concrete wall and the compaction itself. It is also not possible to pour the lost formwork over the entire height of the wall, which causes cracks and nonconnection of the individual concrete layers along the height of the wall. We proposed removing these deficiencies by prefabricating the individual panels directly in the precast using vibratory tables and applying the finished panels to the building structure (Figure 18).

Figure 16. Construction with patented ISOMAX panels [2].

Figure 17. Construction with patented ISOMAX panels [2].

Figure 18. Construction with upgraded panels [1].

The application of the thermal barrier in innovative panels can be on the auxiliary reinforcement in the center of the panel structure (Figure 19, left), or on the outer reinforcement of the panel structure (Figure 19, right).

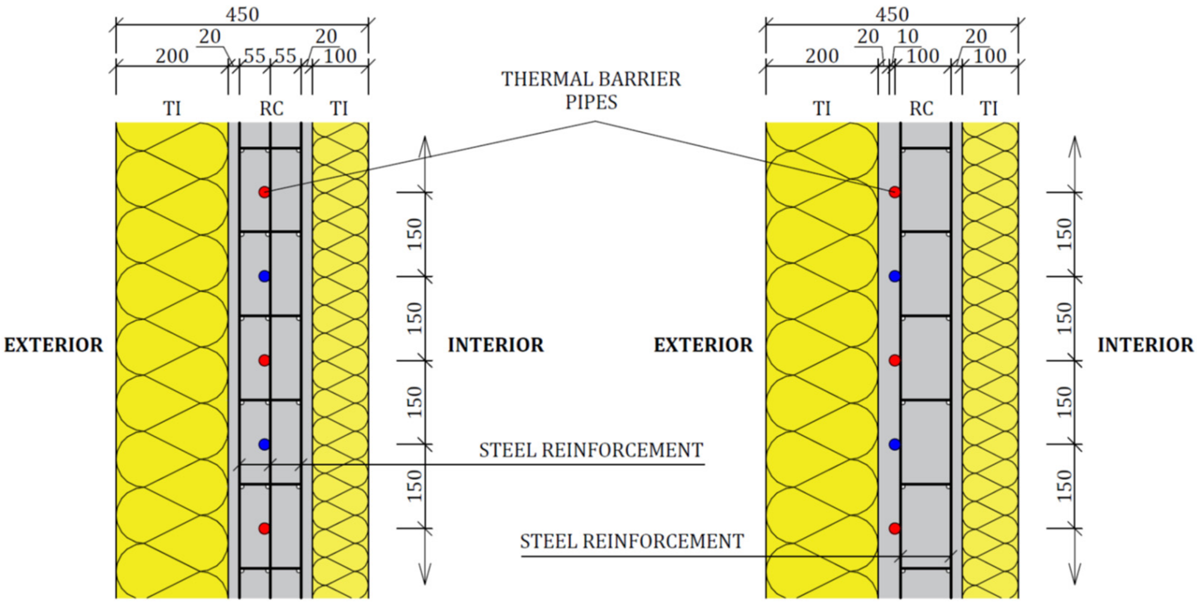


Figure 19. Principle of thermal barrier application in innovative panels (left—thermal barrier pipes are installed on the auxiliary reinforcement in the center of the panel structure; right—thermal barrier pipes are installed on the outer reinforcement of the panel structure). The colored points (red and blue) in the picture are thermal barrier pipes [1].

The prototype of the prefabricated house IDA I was additionally insulated (see Figures 1, 6 and 18). For the complex production of modernized panels already with insulation, a technological procedure has been designed. In the first step, the forms of the panels are created, the interior thermal insulation is inserted, and then the individual layers of reinforcement are created—the distances of which are precisely defined by the auxiliary demarcation elements between each other and the thermal insulation. The next step is to fix the thermal barrier pipes to the reinforcement (center layer or exterior reinforcement layer, Figure 19). Finally, the exterior thermal insulation is inserted, which is also delineated from the panel reinforcement. After these steps, the panel form is closed on all sides, leaving only the upper part of the form free, through which the concrete is poured. Before pouring the concrete, the forms are vertically erected and fixed on the vibrating table.

4.2. Analysis of the Energy Potential of the Retrofitted Panel with a Thermal Barrier Compared to the Original Panel

This technical solution of the building envelope, in addition to the function of a thermal barrier, fulfills the function of a large-capacity heat reservoir. In the mass of the load-bearing part of the walls or roofs made of reinforced concrete, heat/cold is accumulated, which significantly influences the passage of heat/cold through the building structure. When designing the innovative panel, we did not consider the possibility of using concrete with air to increase the thermal properties. In this panel construction, it is important that the load-bearing part is thermally well-conductive to create a uniform thermal layer = thermal barrier and simultaneously have the highest possible heat/cool accumulation capacity. For this reason, we consider the upgraded construction of the envelope panel with a greater thickness of thermal insulation, especially on the exterior side, to be justified and important from energy, economic, and environmental points of view.

The temperature in the thermal barrier of the thermal insulation panel of the envelope can be regulated as required in all four seasons. The role of building structures with integrated energy-active elements (in this case with a thermal barrier) is to actively control the heat transfer through the building envelope (i.e., to adjust the thermal resistance of the building envelope). Our research aimed to design an optimal structure in terms of energy efficiency, economic efficiency, and environmental friendliness.

Sections 3.2 and 3.3 described the compositions of the ISOMAX panel and the upgraded panel designs. Mathematical and physical models were developed and subsequently used to calculate the thermal resistance of the panels R ((m^2·K)/W, the heat transfer coefficient U (W/(m^2·K)) of the panels, the heat transfer coefficients of the external thermal insulation U_{TIe} (W/(m^2·K)), and the temperature θ_j (°C) between the different layers of the panel structures for different thicknesses of the external thermal insulation through a parametric study. Figures 20–24 show a comparison of the most important physical parameters of the ISOMAX panel and the upgraded panel.

The graphs show that, for example, a mean temperature of θ_{TB} (°C) = +15 °C in the thermal barrier layer of this panel design during heating represents the equivalent thermal resistance $R_{equivalent}$ ((m^2·K)/W) or the equivalent heat transfer coefficient $U_{equivalent}$ (W/(m^2·K)) of the panel as would be achieved with a 500 mm thick exterior thermal insulation. By analogy, this can be applied to the cooling period, wherein a mean temperature of θ_{TB} (°C) = +27 °C in the thermal barrier layer for this panel design represents an external thermal insulation thickness of 500 mm.

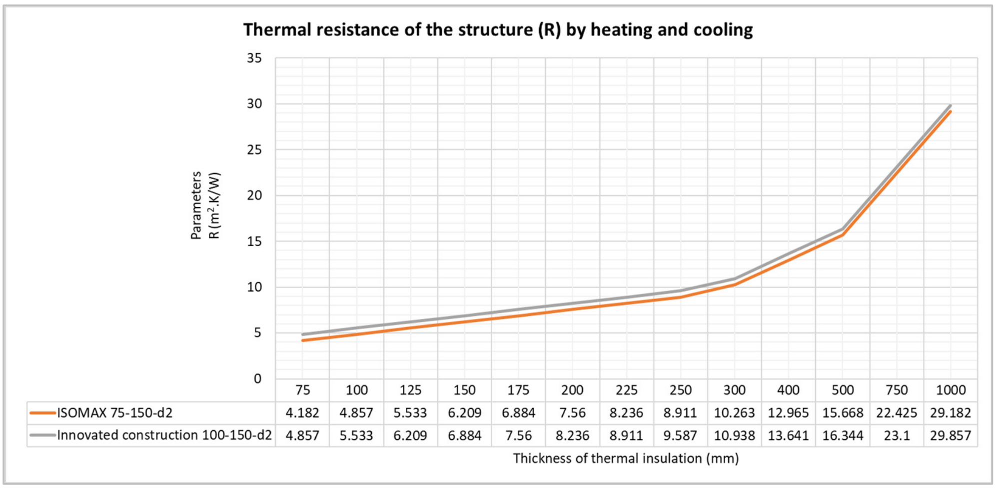
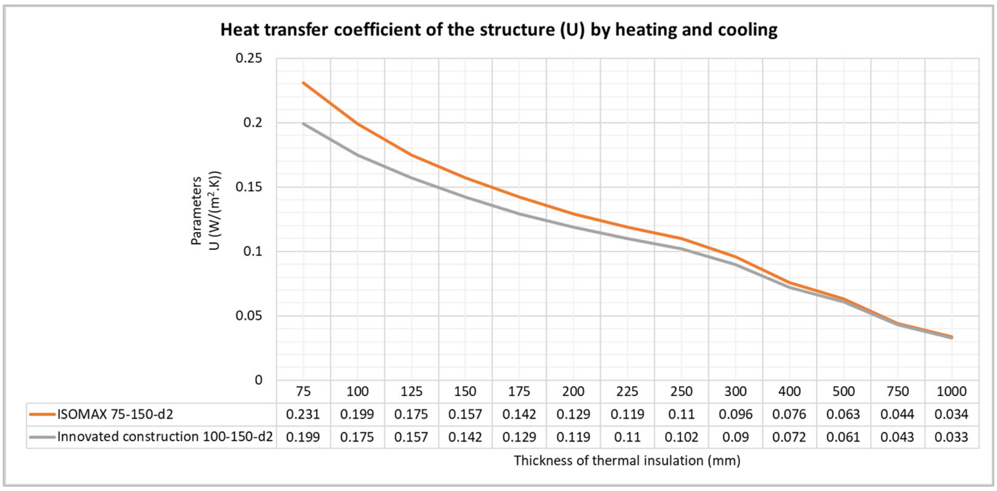
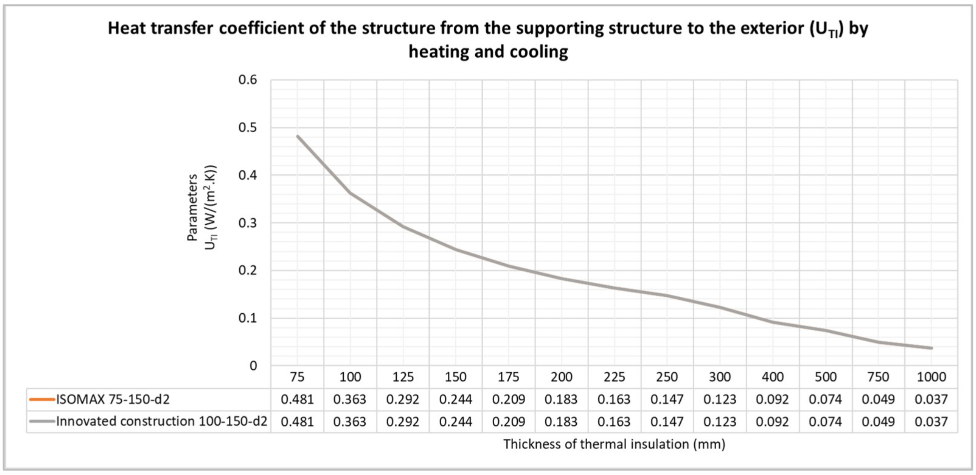


Figure 20. Dependence of the thermal resistance R of the ISOMAX panel and the innovative panel on the thickness of the exterior thermal insulation.



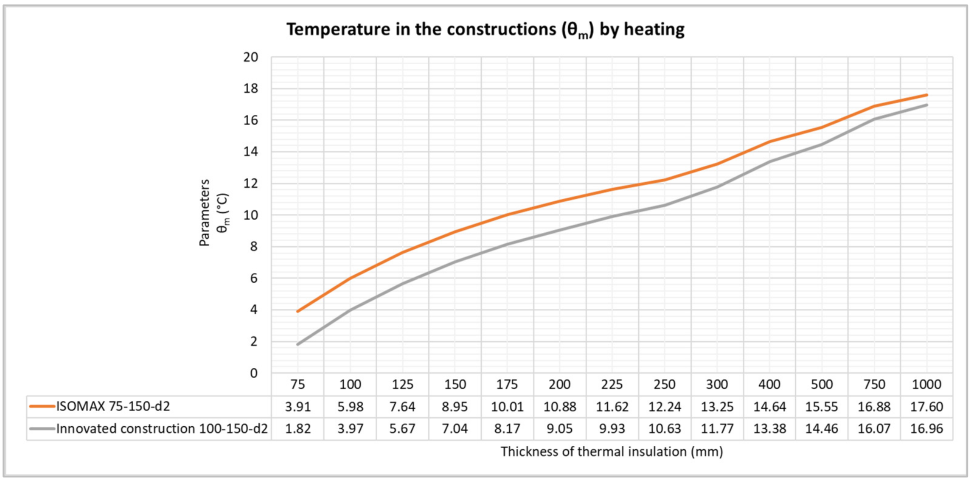
	75	100	125	150	175	200	225	250	300	400	500	750	1000
ISOMAX 75-150-d2	0.231	0.199	0.175	0.157	0.142	0.129	0.119	0.11	0.096	0.076	0.063	0.044	0.034
Innovated construction 100-150-d2	0.199	0.175	0.157	0.142	0.129	0.119	0.11	0.102	0.09	0.072	0.061	0.043	0.033

Figure 21. Dependence of the heat transfer coefficient U of the ISOMAX panel and the innovative panel on the thickness of the external thermal insulation.



	75	100	125	150	175	200	225	250	300	400	500	750	1000
ISOMAX 75-150-d2	0.481	0.363	0.292	0.244	0.209	0.183	0.163	0.147	0.123	0.092	0.074	0.049	0.037
Innovated construction 100-150-d2	0.481	0.363	0.292	0.244	0.209	0.183	0.163	0.147	0.123	0.092	0.074	0.049	0.037

Figure 22. Dependence of the heat transfer coefficient U_{TI} of the exterior thermal insulation on the thickness.



	75	100	125	150	175	200	225	250	300	400	500	750	1000
ISOMAX 75-150-d2	3.91	5.98	7.64	8.95	10.01	10.88	11.62	12.24	13.25	14.64	15.55	16.88	17.60
Innovated construction 100-150-d2	1.82	3.97	5.67	7.04	8.17	9.05	9.93	10.63	11.77	13.38	14.46	16.07	16.96

Figure 23. Dependence of the average temperature θ_m in the thermal barrier layer of the ISOMAX panel and the innovative panel in the heating period on the thickness of the external thermal insulation.

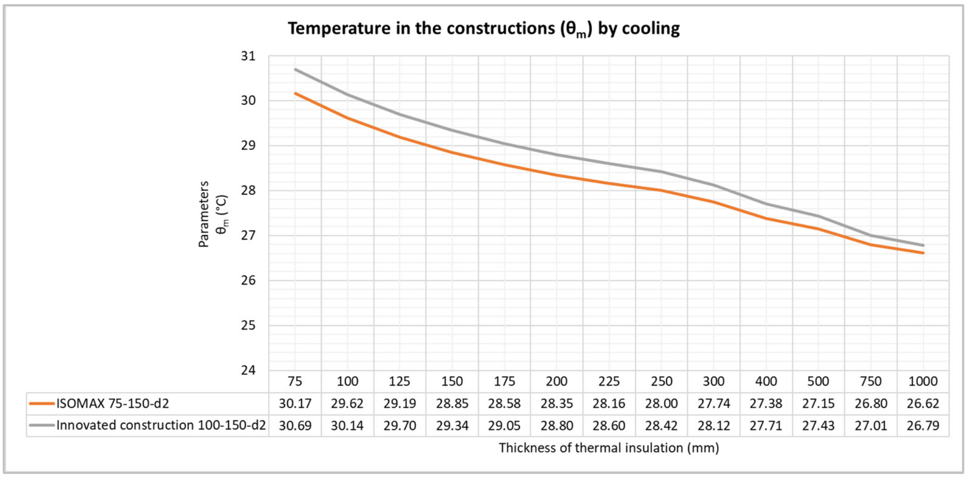


Figure 24. Dependence of the average temperature θ_m in the thermal barrier layer of the ISOMAX panel and the innovative panel during the cooling period on the thickness of the external thermal insulation.

Figures 25 and 26 show the isotherms characterizing the heat transfer through the ISOMAX panel structure and our proposed panel structure in the heating (winter) and cooling (summer) periods. The area between the isotherms of the two designs expresses the heat saving/loss for these alternatives. The area above the isotherms, when heated to a thermal barrier temperature equal to the interior temperature of 20 °C, indicates the potential for heat savings. Similarly, the area below the isotherms, when cooling to a thermal barrier temperature equal to the interior temperature of 26 °C, indicates the potential for cold savings.

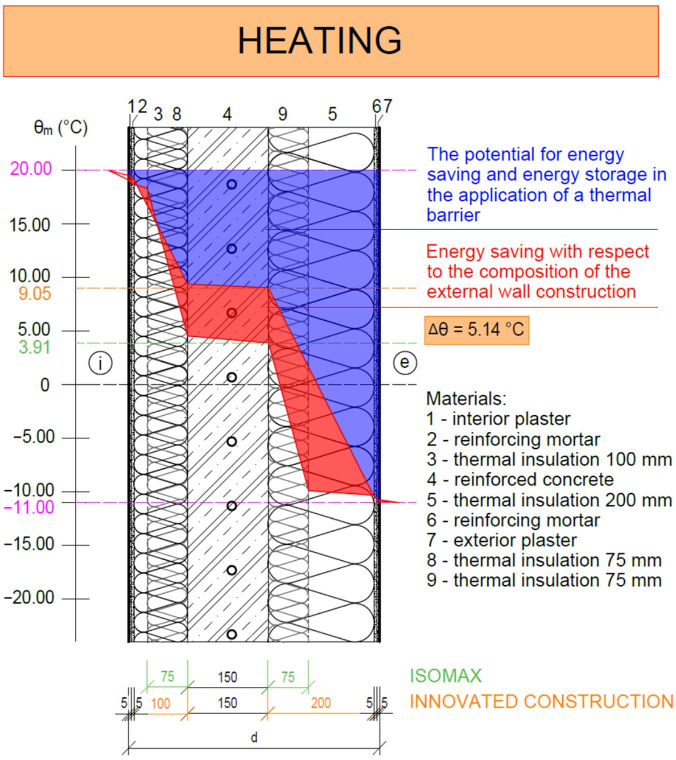


Figure 25. The course of isotherms characterizing the heat transfer through the ISOMAX panel construction and the upgraded panel construction in the heating season. q_i—heat flow towards the interior (W/m^2), q_e—heat flow towards the exterior (W/m^2), θ_i = 20 °C—internal calculation temperature (°C), θ_e = −11 °C—outdoor calculation temperature (°C), θ_{pi}—interior surface temperature (°C), θ_{pe}—exterior surface temperature (°C), $\Delta\theta$—temperature difference, *i*—interior, e—exterior.

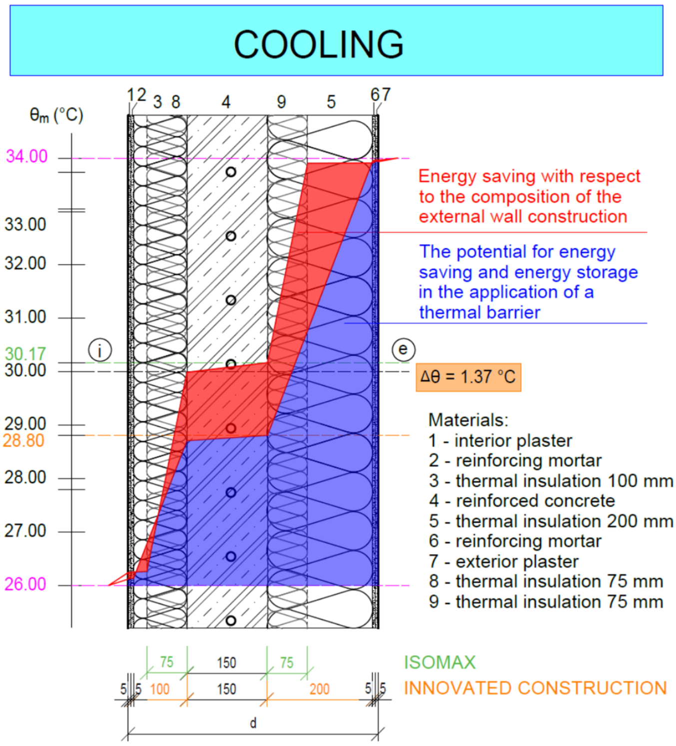


Figure 26. The course of isotherms characterizing the heat transfer through the ISOMAX panel design and the upgraded panel design in the summer period. q_i—heat flow towards the interior (W/m^2), q_e—heat flow towards the exterior (W/m^2), θ_i = 26 °C—internal calculation temperature (°C), θ_e = 34 °C—outdoor calculation temperature (°C), θ_{pi}—interior surface temperature (°C), θ_{pe}—exterior surface temperature (°C), $\Delta\theta$—temperature difference, *i*—interior, e—exterior.

4.3. Synthesis of the Knowledge Obtained from the Scientific Analysis and Transformation of the Data into the Design and Implementation of the IDA I Prefabricated House Prototype

In the following section, we describe the realization of the prototype of the prefabricated house IDA I, wherein we describe the construction part and the energy part of the building in more detail.

The prototype of the prefabricated house IDA I serves as an administrative building and is located in the Vrakuňa district of Bratislava and the site of the Paneláreň Vrakuňa, a.s. plant (Figure 27). The prefabricated house is a two-story building.

Figure 27. Location of the prototype of the prefabricated house IDA I within Bratislava, Slovak Republic. (https://www.google.com/maps (accessed on 20 June 2022)).

4.3.1. Structural System

From a structural point of view, a prefabricated longitudinal load-bearing system was applied, with load-bearing peripheral walls and one central wall formed by reinforced concrete panels (Figure 28). The roof is gable with a ridge parallel to the front façade

(Figure 29). The ground floor contains an entrance hall with a staircase, offices, and sanitary facilities. The attic contains a corridor, offices, and sanitary facilities.

Figure 28. Completion of the ground floor assembly (photo archive: Kalús, D.) [1].

Figure 29. View of the realization of the wooden truss (photo archive: Kalús, D.) [1].

The foundation strips were designed from 450–800 mm wide B-15 concrete, and the underlying concrete was designed from 150 mm thick B-15 concrete reinforced with welded KARI mesh.

The building walls are made of assembled prefabricated panels, which were subsequently insulated with a contact insulation system. The walls with a thermal barrier were designed with thermal insulation on both sides: 100 mm thermal insulation in the interior and 200 mm in the exterior.

The ceiling structures were reinforced concrete monolithic slabs cast into lost formwork. The total thickness of the ceiling slab is 250 mm.

The method of laying the roof covering was dry laying using clamps. Roof ventilation was ensured by breaking the waterproofing film at the ridge and using ventilation tiles [1].

Figure 30 shows a view of the insulated prototype of the IDA I prefabricated house before the final modifications of the external facade [1].

Figure 30. View of the implementation of the insulation of the perimeter panels (photo archive: Kalús, D.) [1].

4.3.2. Energy System

Figure 31 shows a simplified wiring diagram of the technical design of the energy systems of the IDA I prototype prefabricated house. The prototype of the panel house contains a solar energy absorber (i.e., an energetic solar roof) which was designed from 20 × 2 mm, or 16 × 2 mm PP pipes, with lengths of 100–120 m. This system is connected in the attic space to the distributor and collector.

The panel house also contains an underground heat storage tank, accumulating solar energy captured by the solar absorbers. The ground heat reservoir consists of three zones: two located under the base plate and the third zone located directly in the base plate. Excess heat from the heating water tank or directly from the fireplace with a hot water heat exchanger is also stored in the third zone located in the base plate. Individual zones are designed with 20 × 2 mm PP pipes with lengths of 120–200 m.

Low-temperature radiant heating is designed for heating. To eliminate thermal gains and losses, thermal barrier circuits were integrated in the perimeter construction. These systems are connected to the distributor and collector located in the space under the stairs. All other heat and cold sources and energy systems are also connected here. The building's control system cabinet, pumps, expansion vessels, and control valves are also located here.

An energy roof connects the individual circuits of the energy systems: an underground heat storage tank, a peak heat source—a fireplace with a hot water heat exchanger, and a heating water storage tank equipped with an electric heating insert. This is so that the supply of the necessary energy for heating is possible at any time and from any heat source. The circuits of the thermal barrier are also connected to liquid circuits stored in the ground outside the building, which are mainly used for passive cooling.

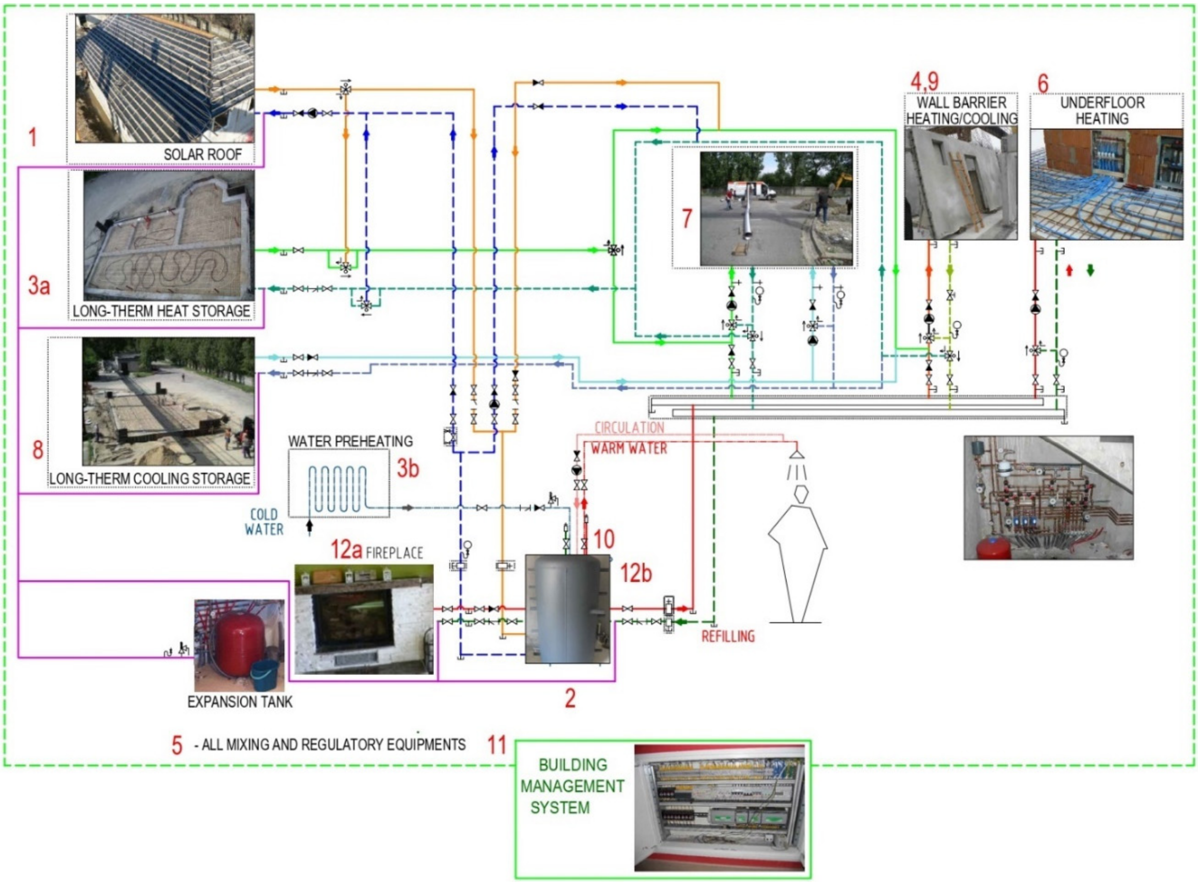


Figure 31. Simplified wiring diagram of the technical solution of the energy systems of the IDA I prefabricated house prototype [1]. 1—solar absorber (energy/solar roof), 2—short-term heat storage, 3a—long-term heat storage, 3b—long-term heat storage, 4—active thermal protection circuits (building structure with an internal heat source), 5—mixing and control equipment, 6—low-temperature heating circuits, 7—heat recovery ventilation equipment, 8—cooling circuits located in the ground outside the building, 9—high-temperature cooling circuits, 10—waste heat from the drainage system, 11—building control system, 12a—fireplace, 12b—peak heat source. The red and green arrows in the figure represent the direction of flow of the heat transfer fluid.

In the building, a pipe-in-pipe countercurrent recuperation exchanger (ISOMAX system) was designed, which was made of a special stainless-steel pipe with an antimicrobial surface of DN 180 for the inner pipe and DN 250 for the outer pipe.

The air supply to the rooms was solved using a plastic distribution under the base plate directly from the combined distributor and air collector on the first floor. On the second floor, the supply distributions are embedded in the thermal insulation of the floor. Air extraction on the first and second floors is handled through the pipe in the soffit.

An underground cooling circuit was designed for cooling the building—the pipes were made of PP 20 × 2 mm, and it was placed outside the building at a depth of 2 m below the ground level. The cooling system is connected through the distributor and the collector to the thermal barrier circuits in the external perimeter walls and also to the heat exchanger in the ventilation air cooling pipe.

A two-stage preparation of hot water was proposed. First, the water in the ground heat storage tank is preheated from a temperature of about 10 °C to about 25–30 °C. The hot water is then heated to the required temperature of 55 °C to 60 °C in a trivalent heating water tank with an integrated hot water tank (which uses solar energy), heating the water in a hot water exchanger in the fireplace or electricity.

After the completion of the assembly work, all necessary pressure and tightness tests were carried out. Both the heating systems (floor heating) and the thermal barrier were hydraulically regulated, the operating values of the control devices were set, and they were subjected to verification of functional characteristics.

5. Conclusions

Based on this study, we can draw the following conclusions:

- The analysis and synthesis of the knowledge from the production and implementation of ISOMAX panels have determined the shortcomings of these panels. We have designed and developed innovative panels that eliminate the lengthy and complicated production as well as on-site implementation. We eliminated the static problems associated with insufficient concrete compaction when the original panels were poured on-site by fabricating the panels on vibratory tables in the panel factory;
- The thermal barrier is one of the functions of building structures with integrated energy-active elements;
- From the review of the scientific literature, it is clear that this is a very progressive area of research. So far, most studies on active thermal protection are based on calculations, computer simulations, and experimental measurements. Few studies have focused on the economic and environmental aspects of the use of active thermal protection;
- For the analysis of both the ISOMAX panel and the upgraded panel, we developed mathematical–physical models and analyzed the energy potential of both panels based on a parametric study;
- The analysis shows that, for example, a mean temperature of θ_{TB} (°C) = +15 °C in the thermal barrier layer of this panel design during heating represents the equivalent thermal resistance $R_{equivalent}$ ((m^2·K)/W) or equivalent heat transfer coefficient $U_{equivalent}$ (W/(m^2·K)) of the panel—as would be achieved with a 500 mm thick exterior thermal insulation. By analogy, this can be applied to the cooling period, where a mean temperature of θ_{TB} (°C) = +27 °C in the thermal barrier layer for this panel design represents an external thermal insulation thickness of 500 mm;
- The energy analysis and design of the upgraded thermal barrier panel show an energy potential of the thermal barrier and heat/cold accumulation in the mass of the reinforced concrete load-bearing part of the panel. The potential was up to 2.6 times higher than that of the panel in the original ISOMAX design of the system;
- The results of the analysis of the innovative panel design with integrated energy-active elements show high potential for the use of RES and waste heat with the technology;
- In addition to a higher equivalent thermal resistance compared to the ISOMAX panel, our innovative building envelope panel has significantly lower requirements for the operation of the circulators, making the building's energy intensity lower, more economically efficient, and more environmentally friendly;
- The ISOMAX panels and the innovative panels with integrated energy-active elements only fulfil the energy functions of a thermal barrier and heat/cold storage. The design of building envelope panels (by application without external thermal insulation) offers additional energy functions, namely low-temperature radiant heating and high-temperature radiant cooling;
- Further variants of the self-supporting thermal insulation panels for systems with active heat transfer control are presented in the utility model SK 5729 Y1 [25];
- Among the most significant results and novelty of our research in this area can be considered the realization of the prototype of the prefabricated house IDA I.

The objectives of our further research are to:

1. Develop further design variants of thermal insulation envelope panels with integrated energy-active elements.
2. Develop a methodology for the installation of envelope panels with ATP.

3. Implement selected types of perimeter thermal insulation panels with integrated energy-active elements on a laboratory building.
4. Apply the proposed calculation methodology, selection, and assessment for selected combined building-energy systems using RES in buildings.
5. Conduct experimental measurements of selected types of building envelope thermal insulation panels with integrated energy-active elements using RES as part of a laboratory building object in different operating modes.
6. Measure usable energy of selected types of thermal insulation panels with integrated energy-active elements using RES in the application of active thermal protection in the functions of thermal barriers, cooling, and preparation of TV or heating water.
7. Measure the efficiency of selected types of thermal insulation panels with integrated energy-active elements using RES in the application of active thermal protection for the elimination of overheating of the envelope and the interior depending on the intensity of solar radiation, shading, and the outdoor temperature.
8. Develop software for designing, calculating, and assessing envelope thermal insulation panels with integrated RES-using active elements.
9. Develop a methodology for applying building envelope thermal insulation panels with integrated RES energy components in a building information modeling (BIM) model.
10. Ensure the automated transfer of the proposed database of envelope thermal insulation panels with integrated energy-active elements using RES to the BIM model.
11. Verify the proposed solution on a concrete building project created in the BIM model.

6. Patents

The novelty of the research described in this study lies in the innovation of the design of the envelope panel with a thermal barrier. Partial results of our research have been published in several scientific articles and are also part of three utility models (UM SK 5749 Y1, [26], UM SK 5729 Y1, [25], and UM SK 5725 Y1, [27]) and one European patent (EP 2 572 057 B1, [28]).

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