

Article

Thermal Performance Evaluation of a Retrofitted Building with Adaptive Composite Energy-Saving Facade Systems

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Abstract: A possible way to solve the problem of energy saving in construction is to introduce energy-efficient buildings at the design stage and, in particular, during retrofit. Therefore, the purpose of this study is to conduct a theoretical analysis of thermal resistance and energy loads on a building in cold climatic conditions. The study of these values was carried out in the ANSYS software package and the Maple computer algebra system, respectively. This study examines four types of structures: the existing facade of a building constructed in 1966, a traditional ventilated facade, and two designs featuring alternating insulation layers with enclosed air channels and with or without heat-reflecting screens in the insulation layer. The results of this study show that the new design incorporating heat-reflecting screens in the insulation layer is 1.15 times more energy-efficient in terms of thermal resistance than the proposed design without such screens. The effectiveness of the proposed new design with heat-reflecting screens in the insulation layer is also confirmed through an analysis of the thermal protection of the building, where the auxiliary indicators, specific characteristics, and complex values of energy efficiency and energy load of the building show greater efficiencies of 1.6, 1.03, and 1.05 times, respectively, compared to the other studied structures. The comprehensive research results presented in this study indicate that the use of energy-efficient wall structures for the retrofit of external enclosures can significantly improve the thermal performance of buildings. It was also determined that the use of such wall structures can significantly enhance the building's overall energy efficiency rating. The findings of this study highlight that the proposed solutions can contribute to significant energy savings in buildings, while the newly developed structures can serve as valuable additions to the existing catalog of energy-efficient external wall designs.

Keywords: energy efficiency; composite facade structure; airgaps; reflective screens; computational fluid dynamics analysis



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1. Introduction

Environmental safety is one of the key priority areas in all countries, where reducing emissions and CO₂ storage are recognized as vital strategies in combating climate change. CO₂ emissions lead to environmental pollution caused by the use of fossil fuels [1]. One of the significant contributors to environmental pollution is the construction sector [2].

Therefore, various measures are being developed in this sector to minimize carbon dioxide emissions into the atmosphere worldwide, including in Asian [3,4], Western countries [5], and, on a nationwide basis, Kazakhstan [6]. According to the data presented in [6,7], buildings account for roughly 30% of the total final energy consumption worldwide, with this figure surpassing 40% in the European Union [6,8]. Heating represents the largest portion of final energy consumption, making up, for instance, 66% in Europe, 37% in the United States, and 54% in China [9,10].

Such solutions are driven by the fact that maintaining a comfortable indoor climate in residential buildings is one of the primary requirements. One way to achieve this is by using energy-efficient envelope structures, such as exterior walls, roofs, and glazing systems [11,12]. This involves using insulation with high thermal resistance, recovering heat from naturally circulating air, sealing wall leaks to reduce air infiltration, and installing high-performance window frames [13–15]. Among various challenges in the construction sector, retrofit has gained particular attention. Around the world [16–19], including in Kazakhstan, a significant number of residential buildings do not meet energy efficiency standards. For instance, according to [20], Kazakhstan's housing sector comprises over 80,000 apartment buildings, with 18,000 of them in need of major renovation [21].

A review of numerous studies shows that upgrading the external enclosures of existing buildings can yield significant energy-saving results. Chen X. et al. [22] carried out a comprehensive study on the energy efficiency of residential buildings in five climatic zones, analyzing three main factors—glazing ratio, architectural form, and spatial arrangement—with a focus on facade retrofit. The results demonstrated that an integrated approach to residential building retrofit reduced energy consumption by nearly half, depending on the region and structural design. Cetiner I. et al. [23] proposed measures for facade renovation using thermal insulation in their field studies. Their research showed that using insulation significantly reduced both energy consumption and environmental impact, regardless of building type and orientation. Paiho S. et al. [24] examined a versatile facade system for renovating aging apartment buildings in cold climates, showcasing substantial energy savings. Similarly, Park H. et al. [25], in their case study of schools built in the 1930s, highlighted the importance of building reconstruction with improved wall enclosures. Their study revealed that thermal conductivity decreased from 1.47 to 0.38 W/m² K and minimizing air leakage resulted in a 29% decrease [26]. Alosan M. et al. [27] conducted a comprehensive optimization analysis of educational building facades under extreme hot climate conditions, identifying the most effective retrofit strategies. Their findings suggest that these strategies can lower cooling loads by up to 17%, cut lighting energy consumption by 49%, and reduce annual electricity expenses by 18%. The importance of modernizing historic buildings for energy conservation was also explored by Kyritsi E. et al. [28], who achieved up to 49% in energy savings in the Presidential Palace, resulting in a reduction of 259.9 tons of CO₂ emissions. Similar positive results were obtained in [29] during the renovation of a church, confirming the significance of retrofit regardless of building type. As highlighted in the literature review in Table 1, building retrofit places special emphasis on external facades, which must meet various requirements such as durability, aesthetics, energy efficiency, and cost-effectiveness.

Literature Review

Numerous scientific and technical researchers have developed a vast range of new facade enclosures for both new constructions and the renovation of existing structures. An analysis of existing sources, including studies indexed in Scopus, Web of Science, and e-Library, shows that multilayer facades with airgaps are particularly attractive due to their

simplicity and cost-effectiveness [30–32]. Table 1 presents an analysis of the most relevant scientific studies of the influence of geometric parameters of air layers.

Table 1. An analysis of the most relevant scientific studies of the influence of geometric parameters of air layers.

Authors	Year/Type of Study	Analysis of the Obtained Results in the Context of the Authors' Research	Relationships Between Studies
De Masi R.F. et al. [33]	2021/Experimental	It was established that the main factors influencing the ventilated facade were solar radiation and outdoor air temperature, while the influence of wind was negligible.	The study examined the parameters of only ventilated facades using recycled materials.
Jankovic A. et al. [34]	2021/Theoretical and Experimental	A connection was established between the design characteristics and thermophysical processes arising in facade systems with a ventilated airgap.	The study only considered the facade's spatial characteristics with an airgap. The effect of reflective screens was not investigated in the work.
Kuznetsova E.V. et al. [35]	2021/Theoretical	It was established that the use of a ventilated facade was more efficient compared to the traditional “wet” facade, based on the example of a hotel complex construction. A comparison of the costs of required materials and installation was presented.	The study examined the structural parameters of the only traditional facade with a ventilated airgap.
Shahrzad S. et al. [36]	2022/Theoretical	The CFD modeling defined that the use of ventilated facades led to efficiency in fresh air conditioning of 73% in summer and 65% in winter. At the same time, the analysis found that in winter, due to the use of an air layer, the average air temperature increased by 3 °C, while it helped to reduce the extreme temperature by 5 °C during extremely hot summers.	The study examined the parameters of only ventilated facades using recycled materials.
Nizovtsev, M. et al. [37,38]	2022/Theoretical and Experimental	It was found that even with high indoor humidity of approximately 70%, the relative humidity within the insulation material remained below 50%, maintaining the panels' excellent thermal insulation properties due to the presence of ventilated channels.	The research examined the impact of only ventilated channels on the moisture content of a building structure. The effect of reflective screens was not investigated in the work.
Tao Y. et al. [39–41]	2022/Theoretical and Experimental	Two new models with air channels for ventilation were developed. It was established that the new models demonstrated satisfactory result convergence, with a difference of up to 9%.	As a design solution, the study examined the influence of air channels only. The effect of reflective screens was not investigated in the work.

Table 1. *Cont.*

Authors	Year/Type of Study	Analysis of the Obtained Results in the Context of the Authors' Research	Relationships Between Studies
Suárez, M.J. et al. [42]	2022/Theoretical	Various parameters were analyzed, including panel temperature, average air velocity within the cavity, and heat flow paths through the air cavity and into the room.	The study examined the use of airgaps and the influence of their only geometric parameters. The effect of reflective screens was not investigated in the work.
Fu Y. et al. [43]	2023/Experimental	A new method for high-precision thermal evaluation of heat transfer in air channels in actual working environments was proposed.	The study examined the influence of sunlight exposure when the facade system contained only ventilated channels.
Roig O. et al. [44]	2024/Theoretical	The influence of various characteristics of a ventilated facade was evaluated, including the exterior covering material, the relative positioning of the mass and insulation in the main wall, and the geometry of the air cavity. It was established that an air cavity of up to 10 cm led to a reduction in the average heat flux.	The study investigated the influence of ventilated airgaps only and identified the most effective geometric parameters of the airgap.
Domínguez-Torres C.A. et al. [45]	2024/Theoretical	The findings indicated that the design features of the ventilated facade, considering the placement of windows, led to a reduction in heat flow by up to 32% over the annual cycle.	The investigation explored the effect of the correlation between windows and the ventilated facade.
Zhao X. et al. [46]	2025/Experimental	It was established that the configuration of facades with natural ventilation, considering the optimal combination of shutters, led to significant results in terms of air volume flow at the exit of the airgap.	The research analyzed the impact of the connection between shutters and natural ventilation within facades.

Table 2 presents the work that studied thermophysical processes occurring in the layers under the influence of various external factors.

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Authors	Year/Type of Study	Analysis of the Obtained Results in the Context of the Authors' Research	Relationships Between Studies
Pastori S. et al. [47]	2021/Theoretical	Based on CFD analysis, the dependence of the energy efficiency of enclosing structures on solar radiation, the advantages of natural convection in terms of potential energy savings, and the importance of designing an optimized facade geometry were established.	The advantages of natural convection have been established in terms of the potential savings of only traditional ventilated facades.

Table 2. Cont.

Authors	Year/Type of Study	Analysis of the Obtained Results in the Context of the Authors' Research	Relationships Between Studies
Zender-Świercz, E. [48]	2021/Theoretical	The analysis and CFD modeling led to the conclusion that facade ventilation systems were a good way to improve the indoor climate as they effectively reduced air pollution. The decentralized facade ventilation system reduced the concentration of carbon dioxide to less than 1000 parts per million and maintained the indoor air temperature in the range of 19.5–22 °C.	The study performed an analysis of a decentralized device installed on the facade of a building in which the air supply and exhaust cycles were reversed due to the correct location of the dampers
Shao Y. et al. [49]	2022/Theoretical	The use of only enclosed airgaps in the concrete wall structure resulted in an ecological efficiency of up to 44%, which led to a 49% reduction in energy costs.	The study only examined designs with airgaps of the enclosed type.
Rahiminejad, M. et al. [50,51]	2022/Theoretical and Experimental	It was established that increasing the cavity thickness behind the outer cladding from 45 mm to 110 mm could amplify heat flow through the cavity by up to 1.5 times. Additionally, it was demonstrated that applying reflective insulation on the cavity surface could elevate the cladding surface temperature by over 30% compared to a scenario without reflective insulation.	The study has structurally similar features, such as the use of a ventilated airgap and the presence of a reflective coating.
Zhangabay N. et al. [52]	2023/Experimental	It was experimentally established that the simultaneous use of both ventilated and enclosed airgaps with a reflective screen on the facade structure demonstrated effectiveness in energy conservation.	The paper analyzes another type of thermal insulation material. However, no analysis of the thermal protection of the building was carried out.
Zhangabay N. et al. [53–55]	2023/Theoretical	It was established that the simultaneous use of ventilated and enclosed airgaps with a reflective screen in the facade structure demonstrated energy conservation efficiency of up to 15%.	This work analyzes a different category of thermal insulation material. However, the structure's thermal protection was not evaluated.
Karanafti A. et al. [56]	2024/Experimental	It was established that the use of different configurations of airgaps led to significant energy savings of up to 2.6 times, demonstrating the positive effects of using airgaps in multilayer facade structures.	The study examined adaptive solutions to prevent air penetration into the thermal insulation layer.
Barone G. et al. [57]	2024/Theoretical	It was established that the incorporation of airgaps in architectural envelope structures between two layers of concrete material can reduce heating demand by up to 5.49%.	The study examined the use of airgaps between two layers of the facade structure.

Table 2. *Cont.*

Authors	Year/Type of Study	Analysis of the Obtained Results in the Context of the Authors' Research	Relationships Between Studies
Arauz R. et al. [58]	2024/Theoretical	A methodology for assessing the effectiveness of using airgaps for solar energy collection, ventilation, and temperature control in different generalized scenarios of building–environment interaction was developed. The annual efficiency reached up to 25% compared to the traditional closed facade.	The study examined the effectiveness of using airgaps alone for various situations. However, the issue of using reflective screens was not investigated, which could have positively complemented the idea of energy savings.
Fallahpour M. et al. [59]	2025/Theoretical	The proven optimization system could be adapted for DSF design in various climatic conditions and building types. Computer simulation of dynamics (CFD) was performed to estimate the intensity of air flow and air temperature.	It was found that the optimal design provided a maximum mass flow rate of 0.72 kg/s and an average air velocity of 0.06 m/s while minimizing the temperature difference inside and outside the room to 1.04 °C.

The review of studies on the retrofit of residential buildings using airgaps in facade system designs indicates the significant importance of implementing measures to optimize energy consumption for maintaining a favorable climate in living spaces. Moreover, a review of relevant studies related to the authors' research shows that the application of various design solutions in facade constructions with airgaps is limitless, as evidenced by the studies presented in Tables 1 and 2. Therefore, this study sought to conduct an examination regarding the thermal protection of a building based on the developed energy-efficient facade design, incorporating constructive solutions such as the presence of ventilated and enclosed layers and the use of reflective screens in the structure under cold climate conditions. This study is a continuation of the authors' previous works [48,50–52].

2. Methods and Materials

2.1. Geometric and Thermophysical Parameters of the Investigated External Facade Structures

This study examined four types of external facades, with the initial facade construction being the wet-type facade without airgaps from a building constructed in 1966 (Figure 1a). The first comparison variant was a traditional ventilated facade (Figure 1b). The other two comparison variants were facades with alternating enclosed air channels in the thermal insulation layer, a ventilated layer between the insulation and cladding layers (Figure 1c), and a similar construction, but one facade had reflective screens within the thermal insulation layer covering the alternating enclosed air channels, which were made of aluminum foil with a surface emissivity of 0.039 (Figure 1d).

The main thermophysical and geometric facade construction parameters are shown in Tables 3 and 4.

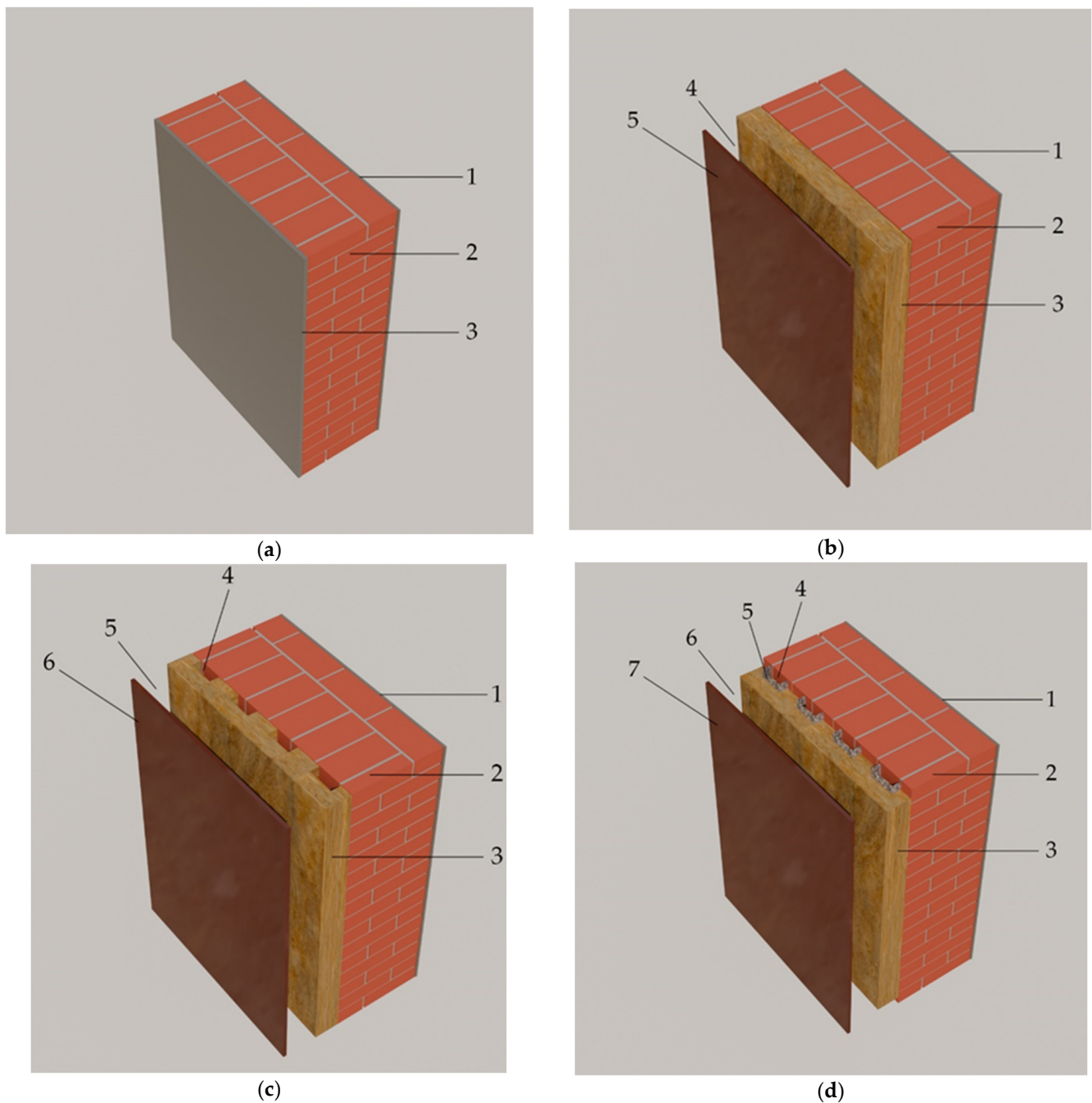


Figure 1. The examined external facades: (a)—an existing wet-type facade without airgaps from a 1966 building; (b)—a traditional ventilated facade; (c)—a facade with alternating enclosed air channels in the thermal insulation layer and a ventilated airgap between the insulation and cladding layers; (d)—a facade similar to (c), but with reflective aluminum foil screens covering the alternating enclosed air channels in the thermal insulation layer. (a) Facade without airgaps: 1, 3—cement-sand render; 2—load-bearing layer made of terracotta brick. (b) Ventiladed facade: 1—cement-sand render; 2—load-bearing layer made of terracotta brick; 3—basalt wool insulation; 4—ventilated airgap; 5—outer cladding. (c) Facade with air channels: 1—cement-sand render; 2—load-bearing layer made of terracotta brick; 3—basalt wool insulation; 4—enclosed air channels; 5—ventilated airgap; 6—outer cladding. (d) Facade with air channels and reflective screens: 1—cement-sand render; 2—load-bearing layer made of terracotta brick; 3—basalt wool insulation; 4—enclosed air channels; 5—reflective screens in the form of aluminum foil; 6—ventilated airgap; 7—outer cladding.

Table 3. Layer characteristics of the facade structures shown in Figure 1a,b.

Layer Number	Description	Thickness, mm	Thermal Conductivity Coefficient, λ , W/(m·°C)	Heat Absorption Coefficient, S, W/(m ² ·°C)	Vapor Permeability, μ , mg/(m·h·Pa)
1	Cement–sand render with a density of 1800 kg/m ³	10	0.76	9.6	0.09
2	Masonry made of terracotta brick with a density of 1800 kg/m ³	380	0.7	9.2	0.11
3	Cement–sand render with a density of 1800 kg/m ³	10	0.76	9.6	0.09
4	Insulation with basalt wool panels on the “DiRock Facade” with a density of 110 kg/m ³	80	0.035	0.3	0.005
5	Airgap	200	-	-	-
6	Cladding layer made of ceramic granite with a density of 2800 kg/m ³	10	3.49	25.04	0.008

Table 4. Layer characteristics of the facade structures shown in Figure 1c,d.

Layer Number	Description	Thickness, mm	Width, mm	Thermal Conductivity Coefficient, λ , W/(m·°C)	Heat Absorption Coefficient, S, W/(m ² ·°C)	Vapor Permeability, μ , mg/(m·h·Pa)	Emissivity Factor of the Heat-Reflective Screen	
1	Cement–sand render	10	-	0.76	9.6	0.09	-	
2	Masonry made of terracotta brick	380	-	0.7	9.2	0.11	-	
3	Cement–sand render	10	-	0.76	9.6	0.09	-	
4	Insulation	Basalt wool panels on the “DiRock Facade” with a density of 110 kg/m ³	105	-	0.035	0.3	0.005	0.039
5		Alternating vertical stripes of basalt wool panels/air	50	100	-	-	-	-
6	Airgap	175	-	-	-	-	-	
7	Cladding layer made of ceramic granite	10	-	3.49	25.04	0.008		

2.2. Mathematical Models and Methodology for Calculating Temperature Fields in Enclosing Structures

To determine the temperature distribution within the enclosure, a finite element approach is applied, where the effect of the ventilated airgap is substituted with a boundary condition of the convective type, with a temperature equivalent to t_{np} . Additionally, a film coefficient parameter, which defines the rate of convective thermal exchange, is set at 1000 [47,56], corresponding to air in motion. On the inner surface of the enclosure, a boundary condition of the convective type is assigned with the lowest allowable mean temperature for the cold season and the highest acceptable temperature for the warm season. The film coefficient, which influences the degree of convective heat flow, is fixed at 10 [47,57], corresponding to sluggish air circulation within the room. The computation

considers the mean temperature of the most frigid five-day span, ensuring a reliability factor of 0.92.

The overall thermal resistance of the enclosing structure may be determined using the equation $R = R_1 + R_2$, where R_2 represents the thermal resistance of the wall, spanning from the airgap to the external atmosphere, the estimation of which is outlined in Equations (1) and (2). In the process of modeling the temperature distribution of enclosing structures incorporating air channels, uniform sections of the enclosure are taken into account.

The case considered in this study is one where the air intake and exhaust occur through one wall. In this case, if we neglect the change in wind speed with height, the air speed in the gap is calculated using the following equation:

$$V_a = \sqrt{\frac{0.08H(t_1 - t_2)}{\sum \xi}}, \quad (1)$$

The air temperature in the gap is calculated using the following equation:

$$t_1 = t_0 - (t_0 - t_2) \frac{x_0}{H} \left(1 - e^{-\frac{H}{x_0}} \right), \quad (2)$$

Equation (2) is a nonlinear ordinary differential equation in terms of t_1 , which is solved using numerical methods. Consequently, the temperature within the ventilated gap, the air speed as per Equation (1), the heat transfer coefficient α_a , and the thermal resistance of the wall from the airgap to the external environment, R_2 , are determined.

The thermal fields in the enclosing elements are determined using the numerical simulation approach within the ANSYS-19.2 software. A computational model of a 1×1 m fragment of the enclosure is developed, where the temperature distribution is computed based on specified ambient conditions. In this scenario, the numerical modeling of the ventilated facade is omitted, and the influence of the ventilated airgap is substituted with the boundary conditions applied to the exterior surface of the enclosure, excluding the ventilated facade from consideration. The process is structured into four sequential phases: 1. Determining the characteristics of the enclosure without accounting for the ventilated facade while incorporating the attributes of sealed cavities and air channels as per [57,58]; 2. Assessing the airflow characteristics within the ventilated facade; 3. Evaluating the thermal field within the enclosure, replacing the ventilated facade with boundary conditions; 4. Determining the characteristics of the sealed gap or airflow channels; and 5. Returning to phase 1 with the revised characteristics of the gaps or channels. The correctness of the selected finite element grid is confirmed by means of the average quality of the model element (Figure 2). At the same time, the authors' previously obtained results [51] based on the analysis of thermal resistance using the presented method are well correlated with the numerical mathematical analysis presented in another study by the authors [60,61], which additionally confirms the correctness of the selected finite element grid in the ANSYS program.

Figure 2 illustrates the facade model and its computational simulation within the ANSYS software environment, corresponding to Figure 1.

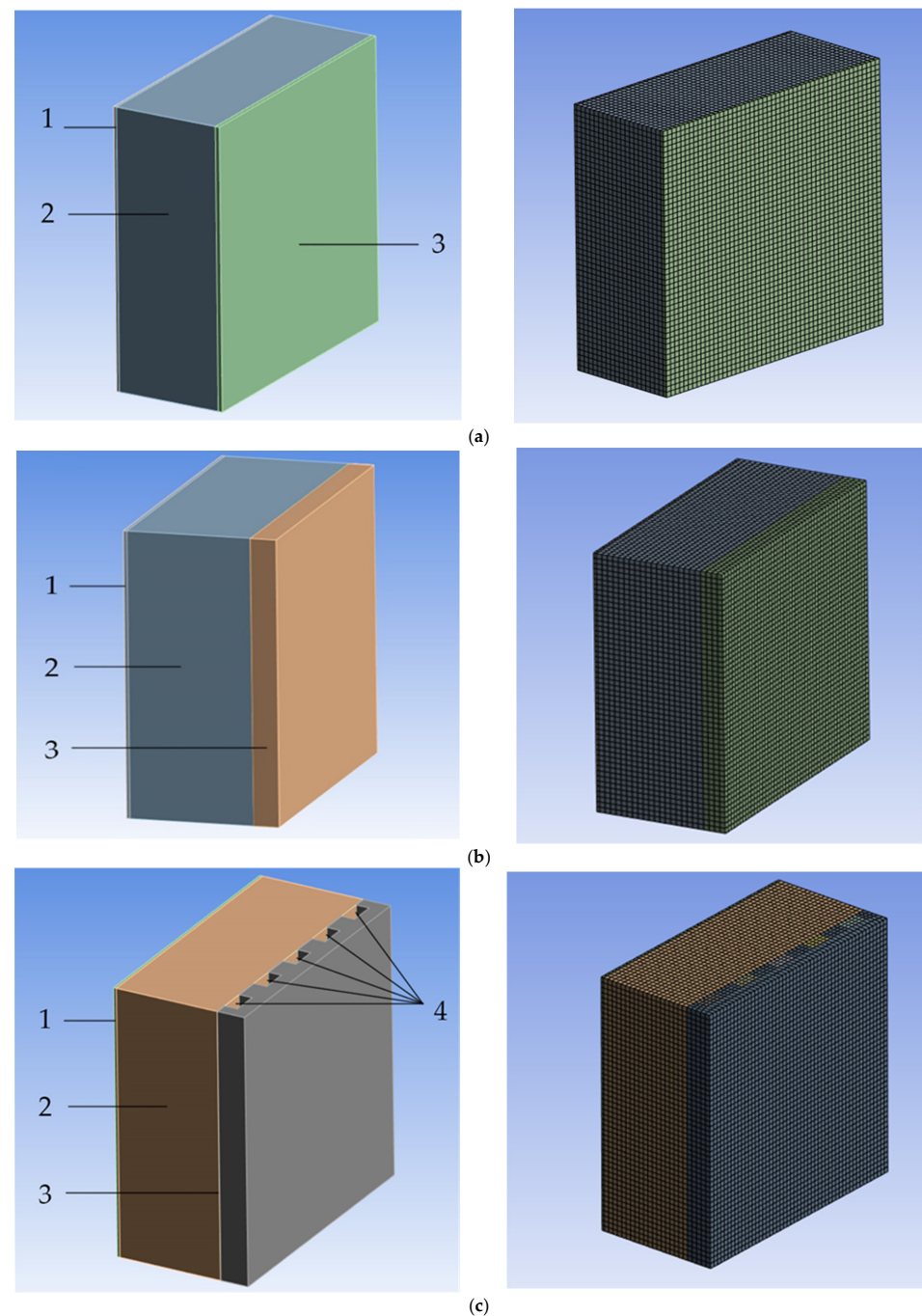


Figure 2. The facade structures and their finite element representation corresponding to Figure 1: (a) representation corresponding to Figure 1a; (b) representation corresponding to Figure 1b; (c) representation corresponding to Figure 1c,d. (a) The model comprises 52,500 hexahedral mesh components with 239,354 connection points. The mean quality of the elements in the model is 0.9867. (b) The model comprises 62,500 hexahedral mesh components with 288,354 connection points. The mean quality of the elements in the model is 0.9816. (c) The model comprises 505,500 hexahedral mesh components with 2,205,074 connection points. The mean quality of the elements in the model is 0.9993.

2.3. Methodology for Evaluating the Thermal Protection of a Modernized Residential Building, Considering the Developed Energy-Efficient Facades

The residential building to be modernized is located in Kazakhstan, in the city of Shymkent. Its general information is presented in Table 5. The external climatic parameters and internal air parameters are presented in Table 6 [62,63]. The structural dimensions of the building are listed in Table 7.

Table 5. General information of the building.

Address of the Building	Shymkent, Kazakhstan
Building purpose, series	Administrative building of Shymkent
Number of floors, number of sections	1, 3
Year of construction	1966
Structural solution	Brick building

Table 6. Calculated climatic conditions.

Name of Calculated Parameters	Calculated Value
Estimated external air temperature for thermal insulation planning, °C	−14.3
Mean external air temperature throughout the heating season, °C	2.1
Length of the heating season, days per year	136
Heating period degree days (HPDDs), °C·days per year	2434
Projected indoor air temperature for thermal insulation design, °C	20
Predicted attic air temperature, °C	Not considered
Assessed crawl space temperature, °C	Not considered

Table 7. Geometric characteristics of the building.

Indicator	Standard Value	Actual Value
Total floor area of the building, m ²	-	171.4
Calculated area (public buildings), m ²	-	102.8
Heated volume, m ³	-	622.3
Facade glazing coefficient	≤0.18	0.17
Building compactness indicator	0.9	0.87
Total area of external enclosing structures of the building, including, m ² :	-	538.91
(1) Walls (separately by construction type)	-	140.2
(2) Windows and balcony doors	-	29.25
(3) Entrance doors and gates (separately)	-	20.0
(4) Attic ceilings	-	174.7
(5) Ceilings over technical basements or unheated cellars	-	174.7

The following presumptions are considered: The absorption coefficient of solar radiation for the outer layer material is 0.5. To determine the airflow characteristics in the ventilated airgap, specifications of the cladding system with 600 × 600 × 10 mm ceramic tiles were applied. The intake opening width is 10 mm. The total of the local resistance factors amounts to 5.4 [64]. The Maple computer algebra system was used to analyze the thermal protection of the building [52].

In Table 8, the methodology for evaluating the thermal protection of the building is presented, considering Sections 2.1 and 2.2 and in line with the facade constructions examined in previous studies [63,65–67]. An explanation of the basic values used in the formulas is provided in the Abbreviations Section.

Table 8. Step-by-step methodology for calculating the thermal protection of the building.

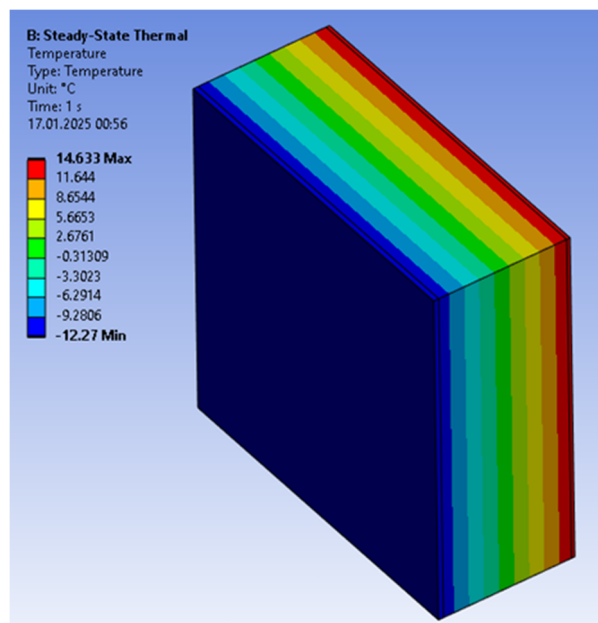
Determination of the Degree Days for the Heating Period	HPDD=(t ₂ −t ₃)z ₁
Thermophysical properties of materials, general information, and geometric and climatic parameters.	The indicated values for the analysis are presented in Tables 1–6.
Thermal performance indicators: determination of the effective thermal resistance coefficient of the walls.	The effective thermal resistance of the walls was determined according to the methodology presented in Section 2.2 using the ANSYS software package, and the results are provided in Section 3.1.
Auxiliary indicators: overall heat transfer coefficient of the building.	$K_1 = \frac{L}{A_1^{sum}} \sum_i \left(n_{t,i} \frac{A_{f,i}}{R_{o,j}^t} \right)$

Table 8. Cont.

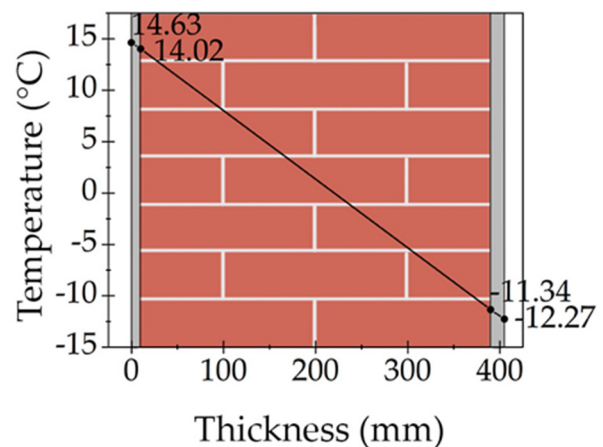
Determination of the Degree Days for the Heating Period	$HPDD=(t_2-t_3)z_1$
Specific indicators: specific thermal insulation characteristic of the building.	$k_1 = \frac{L}{V} \sum_i \left(n_{t,i} \frac{A_{f,i}}{R_{0,i}^1} \right) = K_1 \cdot K_2$
Coefficients	The standard values are presented in Section 3.2 in Table 9.
Comprehensive indicators	$q_1 = k_1 + k_a - \beta_1(k_2 + k_{rad})$
Energy loads of the building	$q = 0.24 \cdot HPDD \cdot q_1^p \cdot h$ $Q_1 = 0.024 \cdot HPDD \cdot V_1 q_1^p$ $Q_2 = 0.024 \cdot HPDD \cdot V_1 (k_1 + k_a)$

Table 9. Values of equivalent thermal resistance of external enclosures versus the type of enclosure.

Type of External Enclosure	Regulated Value, $m^2 \cdot ^\circ C/W$	Calculated Value, $m^2 \cdot ^\circ C/W$ (Figure 3)	Calculated Value, $m^2 \cdot ^\circ C/W$ (Figure 4)	Calculated Value, $m^2 \cdot ^\circ C/W$ (Figure 5)	Calculated Value, $m^2 \cdot ^\circ C/W$ (Figure 6)	Note
External wall	1.42	0.85	2.89	2.64	3.02	Accepted to be in line with Section 3.1
Windows and balcony doors	0.32	0.48	0.48	0.48	0.48	Accepted conditionally
Entrance doors and gates (separately)	1.42	1.89	1.89	1.89	1.89	Accepted conditionally
Attic ceilings	2.4	2.57	2.57	2.57	2.57	Accepted conditionally
Ceilings over technical basements or unheated cellars	2.4	2.43	2.43	2.43	2.43	Accepted conditionally



(a)



(b)

Figure 3. Temperature field in the facade enclosure corresponding to Figure 1a: (a) temperature field model in ANSYS; (b) temperature value diagram of the enclosure layers.

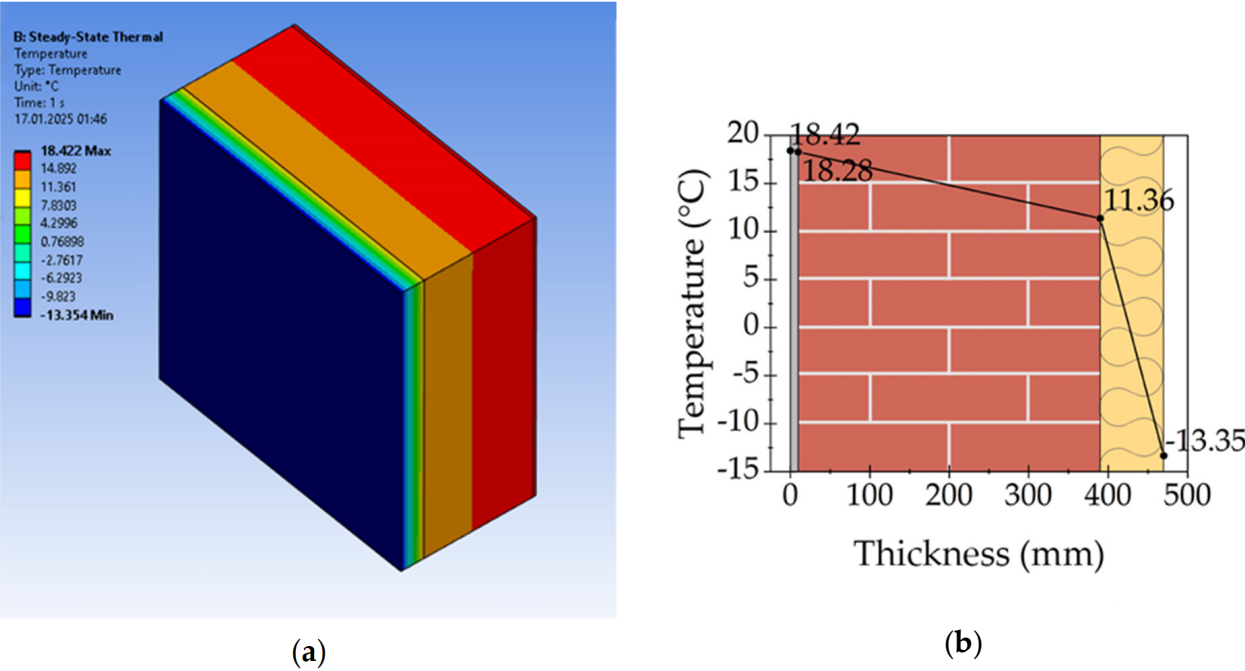


Figure 4. Temperature field in the facade enclosure corresponding to Figure 1b: (a) temperature field model in ANSYS; (b) temperature value diagram of the enclosure layers.

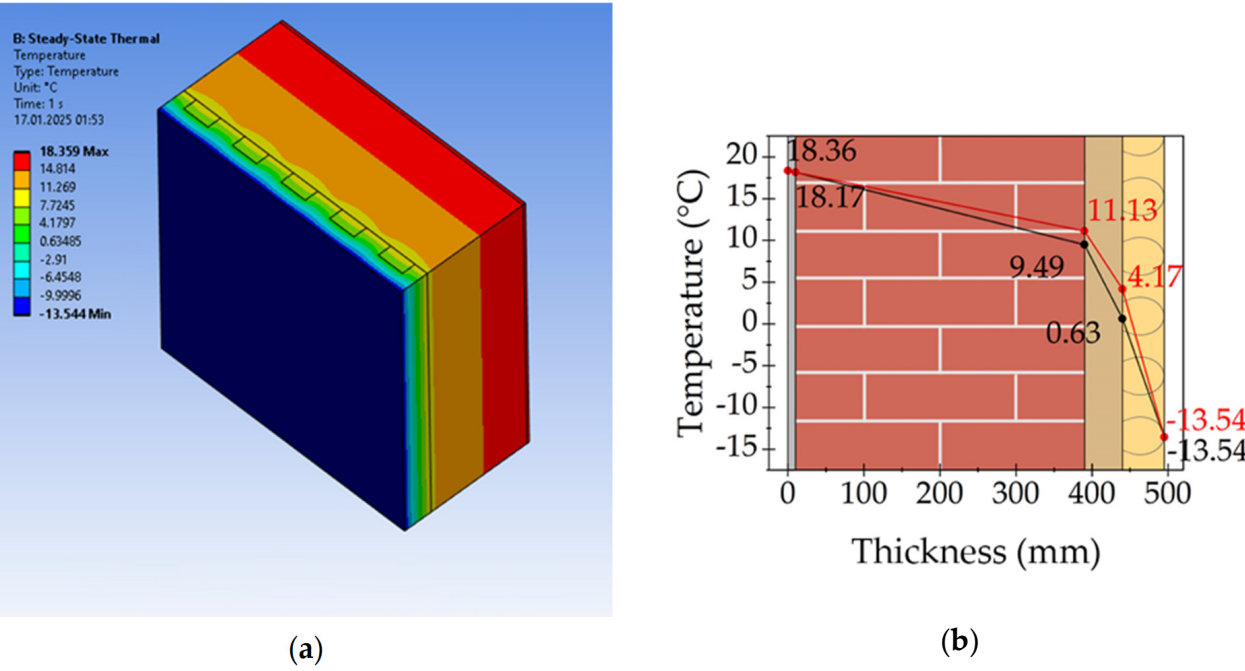


Figure 5. Temperature field in the facade enclosure corresponding to Figure 1c: (a) temperature field model in ANSYS; (b) temperature value diagram of the enclosure layers, with the red line indicating the closed airgap and the black line indicating continuous insulation.

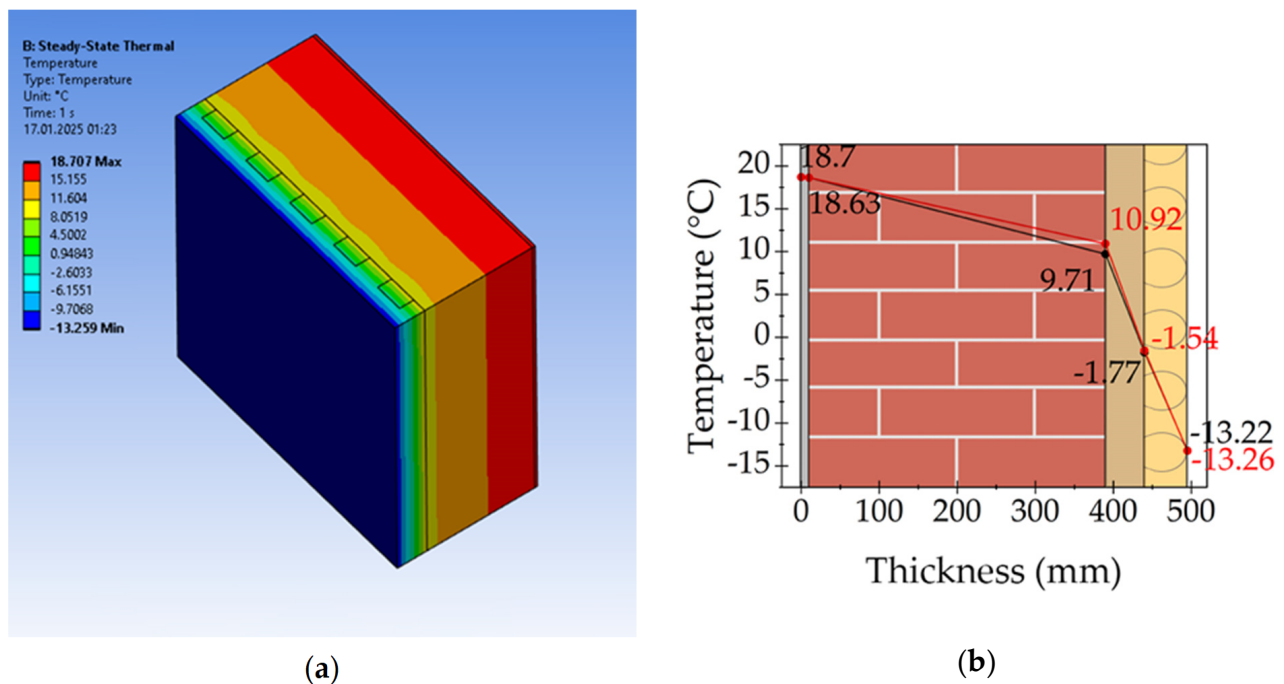


Figure 6. Temperature field in the facade enclosure corresponding to Figure 1d: (a) temperature field model in ANSYS; (b) temperature value diagram of the enclosure layers, with the red line indicating the closed airgap and the black line indicating continuous insulation.

3. Results and Discussions

The results of comprehensive studies are characterized by two main research stages. In the first stage, indicators such as temperature fields and the effective thermal resistance of exterior walls are analyzed. In the second stage, an analysis of the thermal protection of the residential building is conducted, taking into account the developed energy-efficient facades.

3.1. Modeling of Temperature Fields and Determination of Thermal Resistance of the Facade Structures

Figures 3–6 present the results of modeling the temperature fields of the investigated external enclosure facade structures using the ANSYS software package and based on the methodology described in Section 2.2.

Figure 7 presents the result of the thermal resistance analysis of the investigated external enclosure facade structures using the calculation method presented in Section 2.2.

An analysis of the thermal resistance value of the facade structures indicates that the existing wet-type facade (Figure 3) does not comply with the current national standards. According to these standards, the minimum required thermal resistance value for the specified region of Kazakhstan is $R_{tp} = 2.25 \text{ m}^2 \cdot ^\circ\text{C}/\text{W}$ (Figure 7). This non-compliance is due to the fact that the residential building was constructed in 1966, when strict energy-saving requirements were not yet in place. Given that Kazakhstan has since adopted new standards and regulations [68–70], there is a need to modernize the examined residential building. The analysis of retrofit solutions for facade enclosures considers both the traditional ventilated facade structure (Figure 4) and newly developed energy-efficient designs (Figures 5 and 6). The obtained thermal resistance values presented in Figure 7 demonstrate that the thermal resistance of the traditional ventilated facade (Figure 4) is 3.4 times more effective than the existing wet-type facade (Figure 3). The proposed new facade designs, which incorporate alternating enclosed air channels within the insulation layer, with (Figure 6) or without

(Figure 5) heat-reflective screens, proved to be 3.55 and 3.09 times more effective, respectively, compared to the existing facade (Figure 1a). Furthermore, the new facade design with heat-reflective screens (Figure 6) is 1.15 times more efficient than the proposed design without such screens (Figure 5) and 1.05 times more efficient than the traditional ventilated facade (Figure 4), which translates to up to 5% greater efficiency. The analysis demonstrated that the inclusion of heat-reflective screens within the air channels enhances the energy efficiency of the facade structure. It is important to note that there is no significant increase in material consumption for the insulation layer in terms of volume. The only additional material expenditure arises from the heat-reflective screens placed within the alternating enclosed air channels. However, this additional expenditure is minimal and is expected to be offset by energy savings of up to 5% (Figure 6).

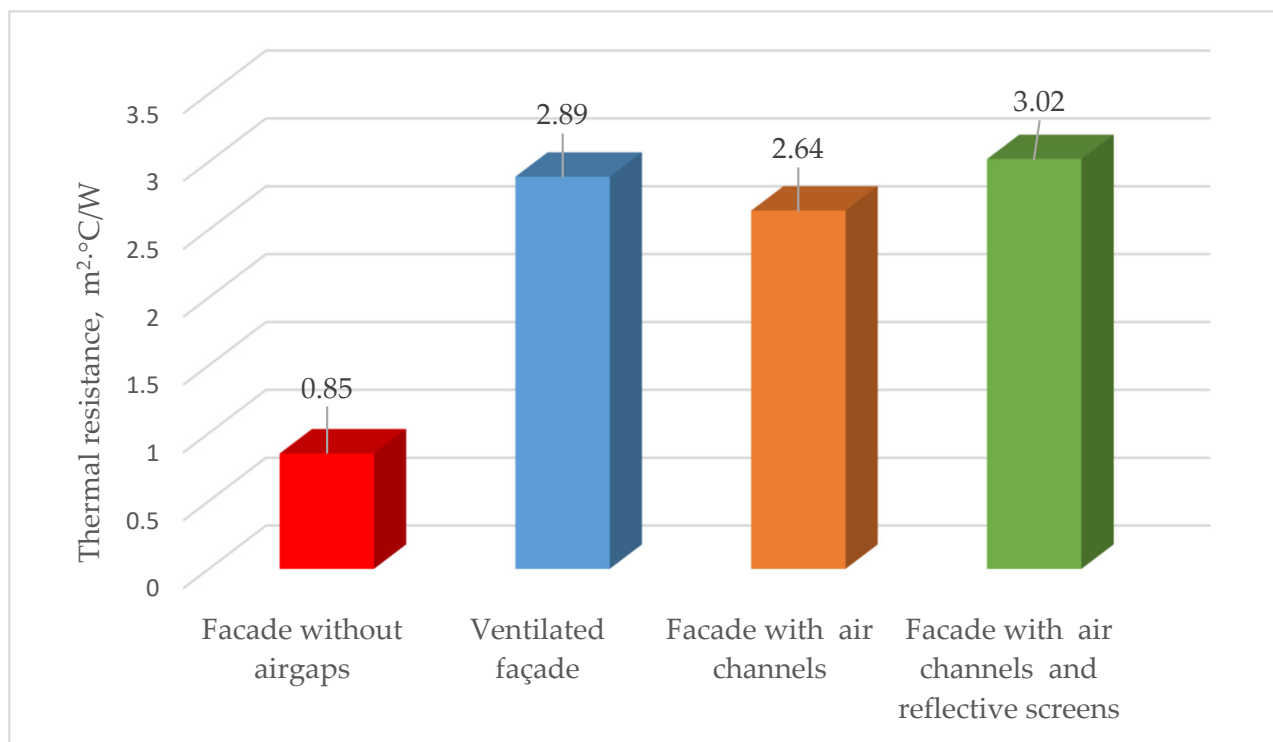


Figure 7. The thermal resistance value of the facade structures.

3.2. Analysis of the Thermal Protection of the Modernized Residential Building, Considering the Developed Energy-Efficient Facades

An assessment of the four facade structures was carried out based on the calculation method presented in Section 2.3. Table 9 presents the obtained and accepted values of the equivalent thermal resistance of external enclosures versus the type of enclosure. Since energy efficiency was analyzed in this study based on the retrofit of the external wall, the values for other external enclosures were assumed to be the same and conditional but no less than the required values outlined in [62,63].

Figure 8 presents the auxiliary values of the building's overall heat transfer coefficient, calculated based on the method described in Section 2.3 and presented in Table 8.

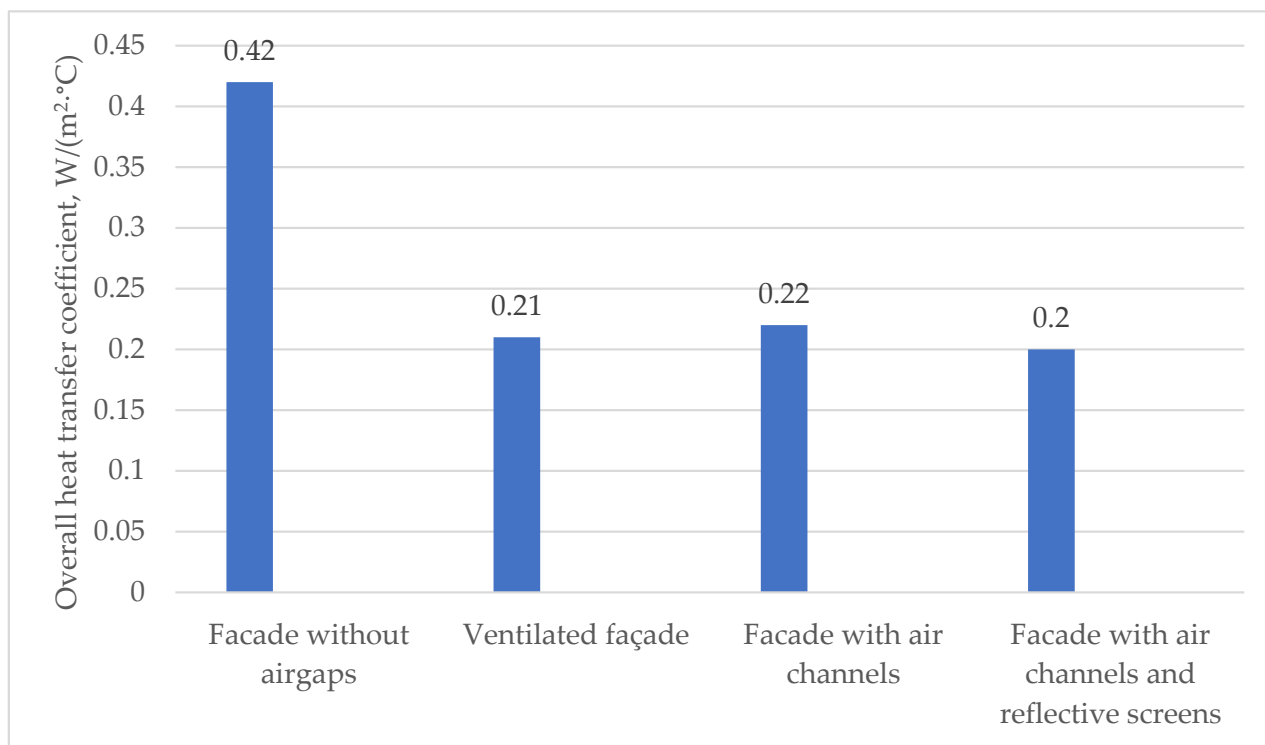


Figure 8. The value of the building's overall heat transfer coefficient facade structures.

Table 10 presents the results of the analysis of the building's specific characteristics, calculated according to the calculation method presented in Section 2.3 and shown in Table 7.

Table 10. Specific characteristics of the building.

Indicator	Regulated Value of the Indicator	Calculated Design Value of the Indicator (Figure 1a)	Calculated Design Value of the Indicator (Figure 1b)	Calculated Design Value of the Indicator (Figure 1c)	Calculated Design Value of the Indicator (Figure 1d)	Note
Specific thermal protection characteristic of the building, $k_{об}$, $W/(m^3 \cdot ^\circ C)$	0.61	0.37	0.18	0.19	0.17	Accepted to be in line with Section 2.3
Specific ventilation characteristic of the building, $k_{вент}$, $W/(m^3 \cdot ^\circ C)$	-	0.25	0.25	0.25	0.25	Accepted conditionally
Specific characteristic of the household heat emissions of the building, $k_{быт}$, $W/(m^3 \cdot ^\circ C)$	-	0.09	0.09	0.09	0.09	Accepted conditionally
Specific characteristic of the heat gains in the building from solar radiation $k_{рад}$, $W/(m^3 \cdot ^\circ C)$	-	0.11	0.11	0.11	0.11	Accepted conditionally

Table 11 presents the necessary accepted coefficients for determining the comprehensive energy efficiency indicators and energy loads of the building.

Table 11. Values of the coefficients for determining the comprehensive energy efficiency indicators and energy loads of the building.

Indicator	Standard Value of the Indicator
Efficiency coefficient of heating self-regulation, ζ	0.5
Coefficient accounting for the reduction in heat consumption in residential buildings with individual heating energy metering, ξ	0.1
Efficiency coefficient of the recuperator, k_{ap}	0
Coefficient accounting for the reduction in the use of heat gains during periods when they exceed heat losses, ν	0.74
Coefficient accounting for additional heat losses in the heating system, β_h	1.13

Figure 9 shows the results of the calculation of the complex indicator of the energy efficiency of the building in the form of heat energy usage for building heating and ventilation throughout the heating season for various external facades (Figures 3–6) in comparison with the traditional one [63].

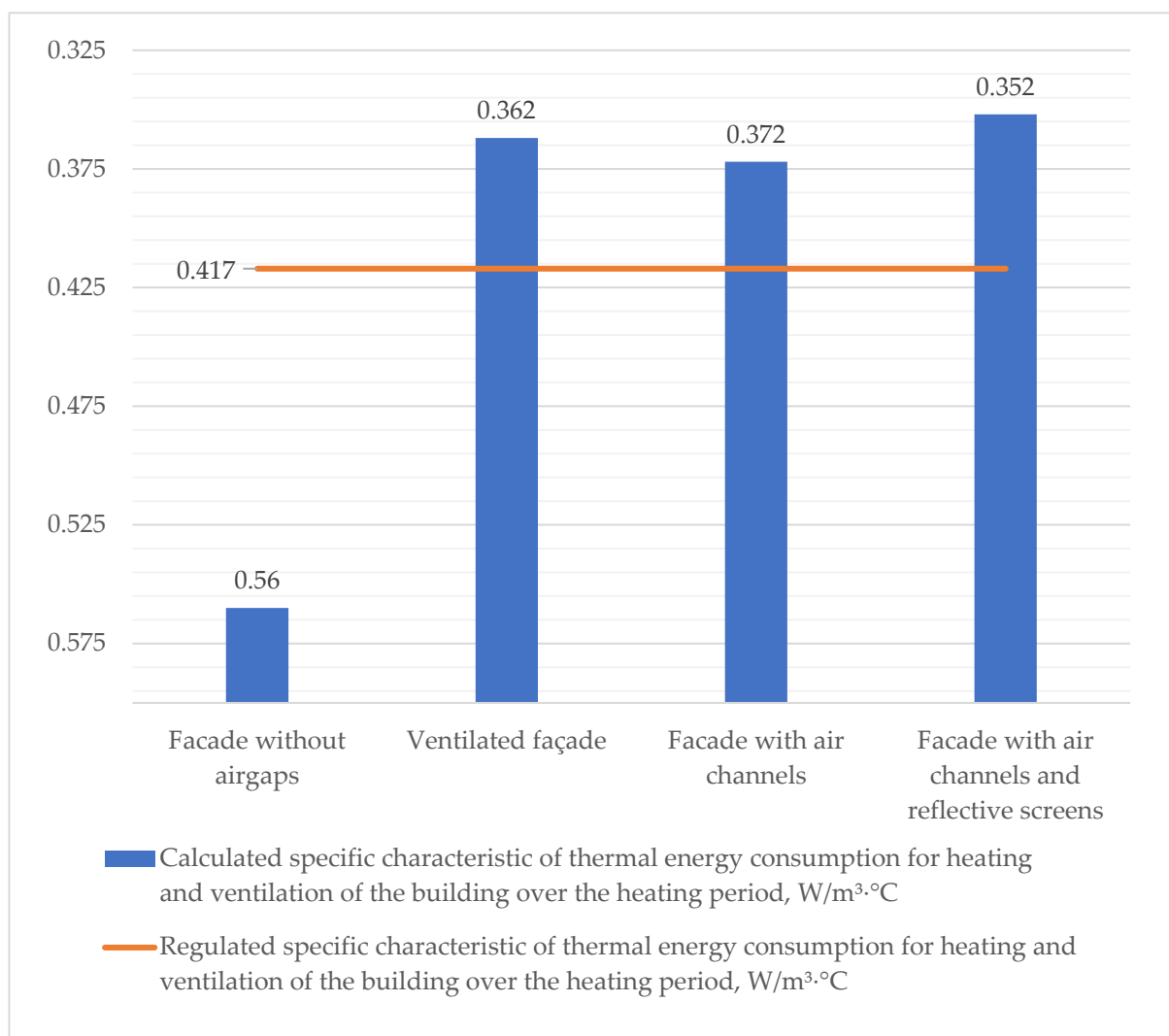
**Figure 9.** Values of the comprehensive energy efficiency indicators of the building facade structures.

Figure 10 presents the results of the calculation of energy loads in the form of the specific thermal energy consumption, the thermal energy usage for building heating and

ventilation throughout the heating season, and the total heat losses of the building throughout the heating period, broken down by types of external enclosures.

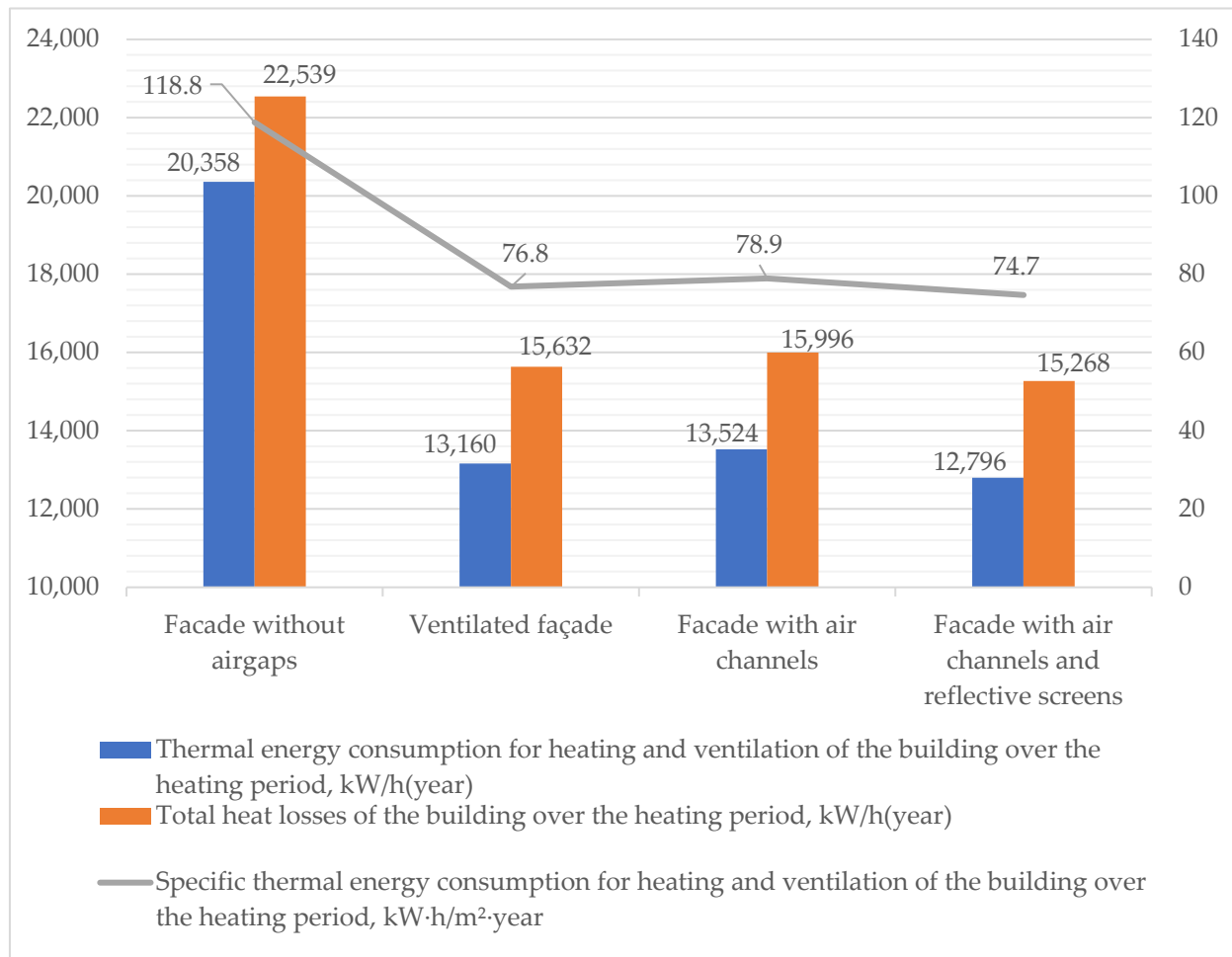


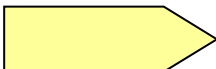
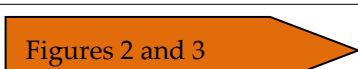
Figure 10. Values of the building's energy loads facade structures.

An investigation of thermal protection for the modernized residential building, considering the developed energy-efficient facades, showed that the proposed design has significant advantages in terms of energy efficiency during the cold period. The analysis focused only on the changes in the external enclosure structure in the form of the external wall, while the other parameters of the exterior enclosure of the proposed designs (Figures 3 and 4) were assumed to be equal and conditional (Tables 9 and 10). Thus, the results of the analysis of the building's overall heat transfer coefficient show that the newly proposed design shown in Figure 4 is the most effective, with its energy efficiency being 2.1, 1.05, and 1.1 times higher, respectively, compared to the other designs in Figures 1–3 (Figure 8). Similar results in terms of effectiveness were obtained in the analysis of the specific thermal protection characteristics of the building, which are presented in Table 10. To further analyze the energy efficiency parameters and energy loads of the building, in line with the standard [63], the corresponding coefficients were determined and are presented in Table 10. The results show that the specific characteristic of thermal energy usage for building heating and ventilation throughout the heating season for the proposed design (Figure 4) is 1.6, 1.03, and 1.05 times more efficient than the designs presented in Figures 1–3, respectively. Moreover, the existing design (Figure 1) does not even meet the regulated value (Figure 9). Similar results regarding the effectiveness of the proposed new design were obtained in the analysis of the building's energy loads, such as the specific thermal

energy usage for building heating and ventilation throughout the heating season, the total thermal energy usage for building heating and ventilation throughout the heating season, and the total heat losses of the building throughout the heating period; these results are presented in Figure 10.

The results of the comprehensive analysis, presented in Sections 3.1 and 3.2, show that the use of energy-efficient wall structures in the retrofit of external enclosures results in a significant enhancement in the building's thermal performance characteristics. It was found that the use of such wall structures can lead to a substantial increase in the overall energy efficiency class of the building (Table 12) [68–70].

Table 12. Energy efficiency class of buildings.

A++ (less than −60%)	Very high	
A+ (from −50% to −60%)		
A (from −40% to −50%)		
B+ (from −30% to −40%)	High (−15.6%)	
B (from −15% to −30%)		
C+ (from −5% to −15%)		
C (from +5% to −5%)	Normal (−12.9% and −10.8%)	
C− (from +15% to +5%)		
D (from +15,1% to +50%)	Reduced (+34.3%)	
E (more than +50%)	Low	

3.3. Discussions of the Study

The need to use air channels is determined by regional climatic features [62,71], as the development of this approach can result in power savings during the summer period in the territories of Kazakhstan, which are positioned in climate zones III and IV [30,62]. This idea is based on the fact that air channels will function as closed channels in the winter period (Figures 3 and 4) and as ventilated channels in the summer period, which will result in power savings in both cold and warm periods due to the thermal protection and thermal stability of the wall structures [71,72]; this is demonstrated in Figure 11.

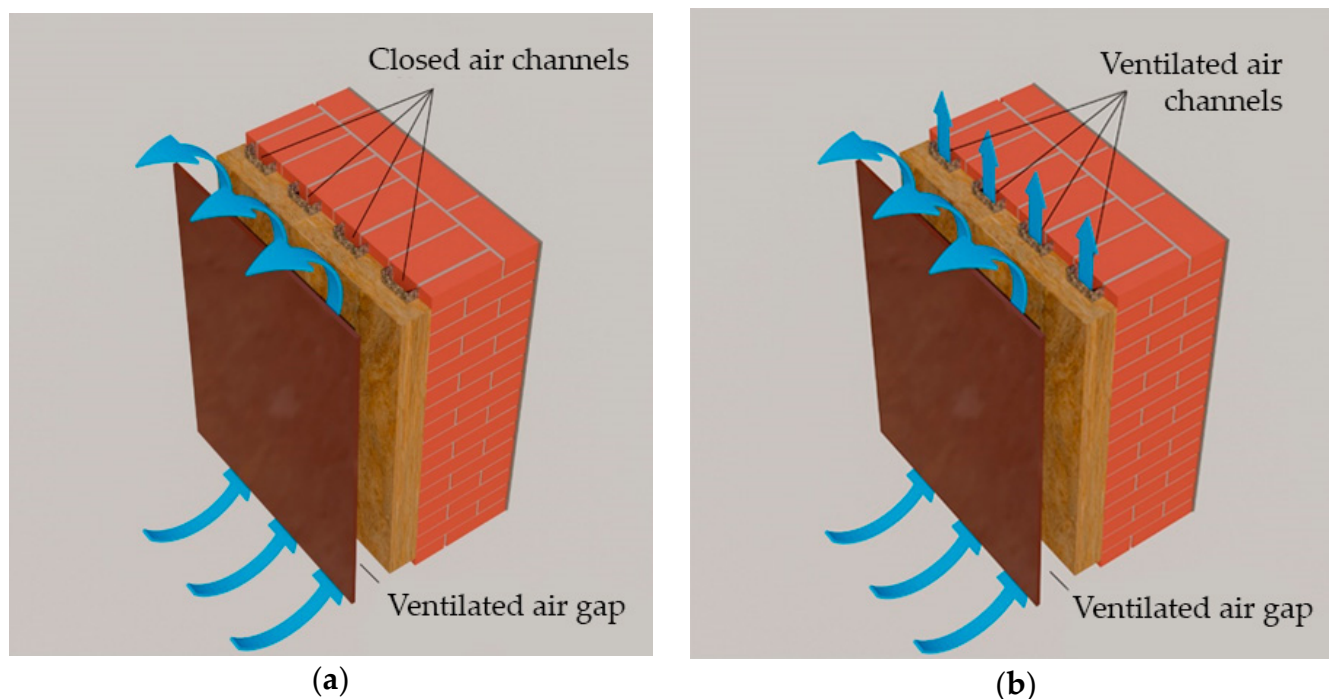


Figure 11. Solution for the new energy-efficient facade design: (a) for the winter period; (b) for the summer period.

Additional studies of this design (Figure 11) during the summer period are required and will be conducted in future works by the authors.

According to previous studies, the use of air layers has a significant impact on the thermal characteristics of external wall structures. An analysis of the conducted research suggests that air layers are used in different design solutions under various climatic conditions, proving to be effective in different ways: economically, in terms of material savings and energy efficiency. These two indicators should logically correspond to real-world conditions. Considering these factors, the authors in this study proposed using their own developed energy-efficient facades with air layers for the retrofit of external wall structures [73], which have already demonstrated their economic reliability in previous studies [48,50–52]. Given the large number of studies on external enclosures, the authors conducted comparisons with similar previous studies in the discussion section. The results of the research analysis indicate that all studies show significant effectiveness when using air layers, with the differences primarily arising from design features (Table 1). The key distinction of the authors' proposed design is the incorporation of nearly all structural solutions that impact energy efficiency in different climatic conditions into a single design. This includes the ability to regulate the parameters of the air layer, which has not been achieved before, as the authors' research aims to analyze adaptive enclosures (Figure 11).

It is worth noting that the results obtained in this comprehensive study will lead to significant energy savings in buildings, and the newly developed designs can positively enhance the existing catalog of external energy-efficient wall structures [74]. As a limitation of the study, it should be noted that the effectiveness analysis was carried out only for the cold period. Additionally, this study considered only stationary heat transfer modes through external facades, meaning the results were obtained based on a single external temperature indicator. For a more comprehensive and reliable analysis, further continuation of this study is needed, incorporating a non-stationary regime approach to complement the current findings. It should also be noted that the external facade structures were modeled only for the cold period, and further research is needed to assess their performance during

the hot period. However, these limitations do not diminish the value of the obtained results. The authors plan to address these limitations in future works by developing an adaptive wall structure that will be energy-efficient under different climatic conditions.

4. Conclusions

This study of building retrofit, considering the use of adaptive composite energy-saving wall structures, revealed that the application of modern adaptive energy-efficient exterior wall systems leads to significant thermal energy savings. An analysis conducted in the ANSYS software of the effective thermal resistance of the proposed new design, compared to existing and traditional ventilated systems, demonstrated that the new structure with heat-reflective screens in the insulation layer is 1.15 times more effective than the proposed design without heat-reflective screens, 1.05 times more effective than a traditional ventilated facade, and nearly 3.6 times more effective than the existing facade built in 1966. Similar results, confirming the efficiency of the proposed new design with heat-reflective screens in the insulation layer, were also shown in the study of the building's thermal protection. The auxiliary indicators, specific characteristics, and comprehensive energy-efficient and energy load values of the building demonstrated efficiency compared to other studied structures by 1.6, 1.03, and 1.05 times, respectively. The results of the comprehensive study presented in this work showed that using energy-efficient wall structures for the retrofit of exterior enclosures significantly improves the thermal performance of buildings. This study also revealed that the regulatory documentation from 1966 concerning the design of exterior facades does not comply with modern requirements, leading to significant energy overconsumption for heating buildings. Moreover, the energy efficiency class analysis established that using the proposed exterior facade designs with air channels and heat-reflective screens during building retrofit upgrades the energy efficiency class from "Reduced" to "High". Thus, the results of this study will positively impact energy savings, contributing to the minimization of environmental pollution. Additionally, these findings can be utilized by scientific and technical specialists when designing new buildings and modernizing existing ones.

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Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

Abbreviations

Acronyms

CFD	Computational fluid dynamics
DSF	Double-skin facade
H	Height difference from the air entry to the air exit in the airgap (typical value is 0.5–0.9 m)
t_2	External air temperature, °C
$\sum \xi$	Sum of local resistance coefficients (depending on the design of the ventilated facade)
t_0	Threshold air temperature in the airgap, °C
x_0	Conditional height at which the air temperature in the airgap differs from the threshold temperature by a factor of e , m
t_3	Average external air temperature during the heating period, °C
z_1	Duration of the heating period, days per year
t_4	Calculated internal air temperature for thermal protection, °C
t_5	Calculated attic temperature, °C
t_6	Calculated crawl space temperature, °C
A	Total floor area of the building, m ²
V	Heated volume, m ³
f	Faced glazing coefficient
A_0^{sum}	Total area of external enclosure structures of the building, m ²
A_1^{sum}	Sum of areas (by internal measurement of all external enclosures of the heated building shell), m ²
$n_{t,i}$	Coefficient accounting for the difference between the internal or external temperatures of the structure and those assumed in the calculation of heating period degree days (HPDDs)
$A_{f,j}$	Area of the corresponding fragment of the building's thermal protection shell, m ²
$R_{o,j}^1$	Thermal resistance of heat transfer for the i -th fragment of the building's thermal protection shell, m ² ·°C/W
β_v	Air volume reduction coefficient in the building, accounting for the presence of internal enclosing structures
K_{rad}	Specific characteristic of heat intake into the building from solar radiation, W/(m ³ ·°C)
k_a	Specific ventilation characteristic of the building, W/(m ³ ·°C)

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