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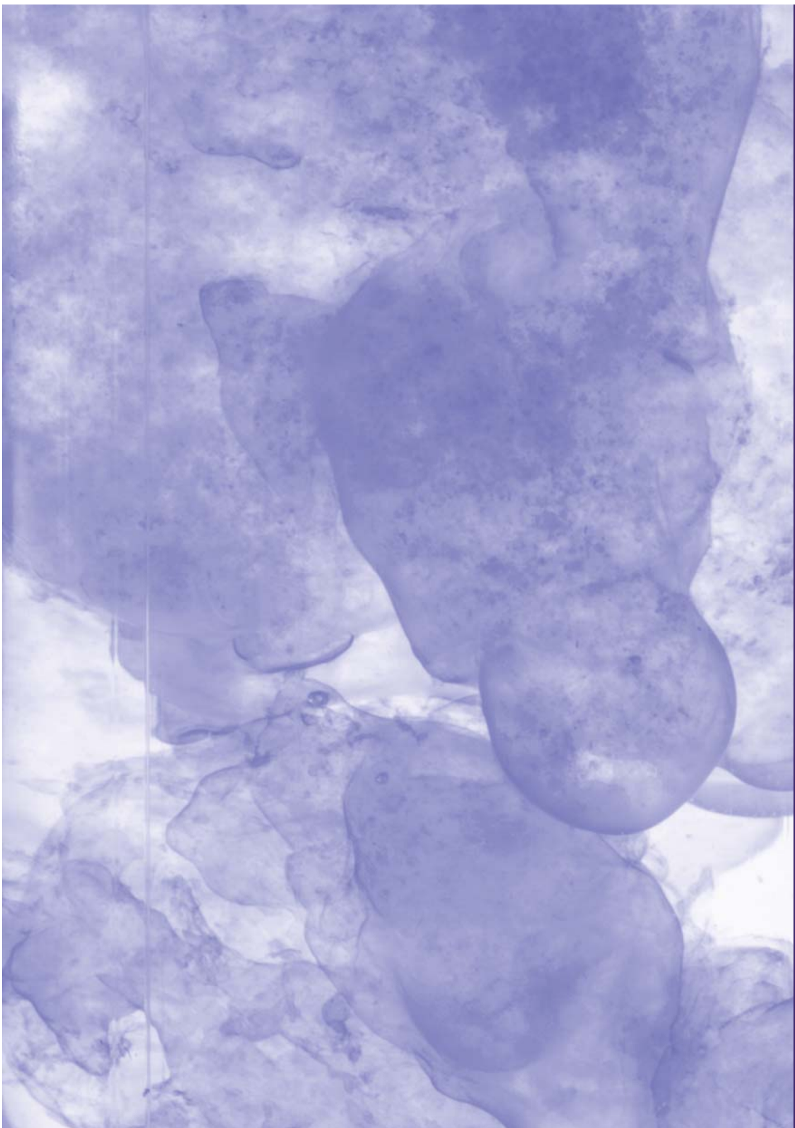

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Prof. Dr. Takayoshi Kobayashi

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Article

Ensuring the Energy Efficiency of Buildings through the Simulation of Structural, Organizational, and Technological Solutions for Facade Insulation

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Abstract: The article presents ways of selecting effective designs and technological and organizational solutions for the bonded thermal insulation systems of complex-shaped facades based on thermal field and flow modeling using the SolidWorks Simulation Xpress 2021 software and experimental–statistical modeling using the Compex program. Determining optimal insulation parameters at the design stage will help eliminate the negative effects of thermal bridges at balcony junctions and reduce the cost of implementing bonded thermal insulation systems for facades with complex shapes. It has been established that the most effective approach is to insulate not the entire perimeter of the balcony slab, as required by normative documentation, but rather to insulate a sufficient portion of the exterior wall, which is equal to 750 mm, with a 30 mm insulation thickness on top of the slab and 50 mm beneath it. This insulation technology is economically feasible for modern multistory buildings with nonstandard volumetric and architectural solutions, constructed using frame–brick, frame–monolithic, or monolithic schemes without thermal breaks between the balcony slab and the monolithic floor slab, with open-type balconies, bays, or uncovered loggias.

Keywords: bonded thermal insulation systems; modeling; temperature fields; optimization; high-rise buildings; duration of insulation; means of paving

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1. Introduction

Currently, the problem of increasing the thermal insulation characteristics of building envelopes has received special attention due to several particularly important reasons, among which are problems of global scaling and local problems in Ukraine. Also, there is the energy crisis that arose at the beginning of the 20th century, which affected not only the states of the post-Soviet period but also the countries of Western Europe, as well as the demands of the international community, including the Kyoto Protocol signed in 2005 in Japan and the Paris Protocol signed in 2015 in France aimed at improving environmental safety by reducing greenhouse gas emissions, etc. [1–3]. Among the main reasons that gave rise to the problem in Ukraine, one can highlight the increased requirements of regulatory documents on heat transfer resistance. So, if before 1996 this indicator was 1.0–1.2 m^2 K/W, in 2013, it was 2.8–3.3 m^2 K/W, increasing by more than 2.8 times. And in 2023, this indicator is already 3.5–4.0 m^2 K/W [4]. At the same time, users of buildings also want to have comfortable living conditions, namely normal heat and humidity conditions and high fire safety in residential premises.

It is known [5] that facade systems with plaster decoration are mostly used during the mass construction of buildings with various structural schemes. This choice of facade insulation technology is based on one of the main reasons for their installation—lower prices compared with ventilated facades.

Some works aim to compare the thermal performance of a polylactic acid 3D-printed block with an internal honeycomb structure whose air cavities are filled with natural and recyclable waste-insulating materials [6] and expanded vermiculite [7]. Lightweight mortar with foamed geopolymer reinforced by recycled-glass-fiber-reinforced plastic fiber is used to decrease shrinkage and increase thermal productivity [8]. Vacuum insulation panels with fibrous porous material provide significant adiabatic performance for heat/cooling systems to reduce energy consumption [9]. The objective of some research [10] is to summarize the efficiency of industrial waste as a pozzolan alternative for cement replacement in foamed concrete production. The disadvantage of using these materials is an inability to insulate certain parts of the existing building that lose temperature the most.

In the work in [11], insulation materials that use recycled rubber in their composition were studied, along with others for comparison: heat-pressed rubber, rubber cork composites, aerogel rubber composite, silica aerogel, and extruded polystyrene. A strategy for wood chip reuse through the fabrication of bio-based building insulation foam was proposed [12]. The results of the research [13] show that it is possible to produce glass foams with thermal and acoustic insulation properties from a mixture consisting of 96.5% glass waste, 1% textile waste, and 2.5% manganese dioxide, processed at temperatures between 800 and 900 °C for a time between 30 and 90 min. In the study in [14], a two-factor experiment was conducted to investigate the influence of accelerator dosage and fiber dosage on the strength, frost resistance, wear resistance, and shrinkage of repaired steel-fiber-reinforced concrete for rigid road surfaces.

Therefore, protruding parts of buildings must be insulated by known methods. To solve this problem and meet the requirements of regulatory documents, the insulation would be better with the help of dense (140–160 kg/m^3) mineral wool or, as a last resort, expanded polystyrene with a density of more than 25 kg/m^3 [15]. However, taking into account the fact that thermal insulation in such places is quite time-consuming and expensive, many developers, despite the requirements of regulatory documents, do not arrange it at all.

There are plenty of methods to research the thermal productivity of materials. The relationship between several important parameters of the phase change wall can be established by using numerical simulation methods [16]. Also, the laboratory experiment can be proceeded [17] using casting and compression mounting methods. Experimentally validated simulations can be performed [18] on a model of a full-scale residential house using the multiphysics software ANSYS FLUENT 2019 R2.

Solving the problem of energy saving will allow for largely reduced energy dependence on countries supplying fuel and energy resources, as well as reduce the energy intensity of national goods. It is known that the construction industry is one of the most energy-intensive, with significant energy expenditures for both the creation of a construction facility and for its operation throughout its entire life cycle.

Under such conditions, a special place is occupied by the problem of thermal insulation of enclosing structures both during new construction and in the process of refurbishment or thermal modernization of residential facilities. Thus, from the mid-1950s to the present time, a huge number of buildings have been erected that do not meet the requirements of modern regulatory documents for thermal insulation of enclosing structures [19,20].

Having analyzed the construction industry, it can be said with confidence that more than half of the buildings built or under construction in Ukraine require an integrated approach to solving this pressing problem, namely increasing the energy efficiency of buildings and structures. In turn, the change in technological conditions for heating houses, due to the need for maximum energy saving, has led to the emergence of massively uncomfortable operating conditions for residential buildings—the presence of low air temperatures, high humidity, and carcinogenic fungal formations on the internal surface of structures and in the indoor air. These issues require immediate resolution through enormous social significance. When analyzing the operational properties of buildings, attention should be paid not to energy saving but rather to their energy efficiency [12,19,20].

The problem should be solved not only based on economic considerations. The scientific approach should be used and justified by the search for optimal models of organizational and technological solutions to ensure the effectiveness of thermal insulation systems for facades.

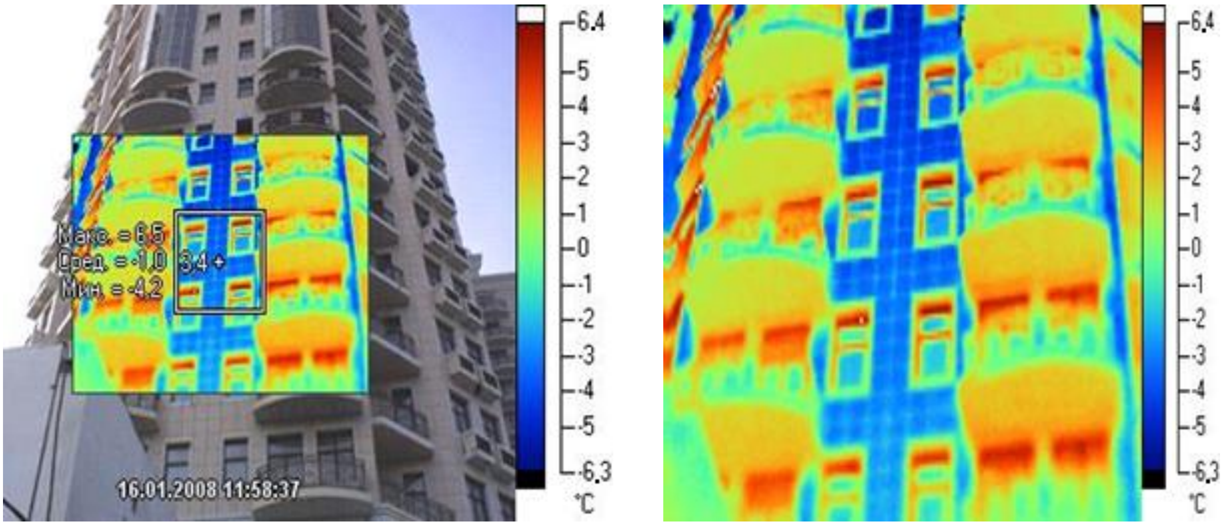
Some of the main tasks in the construction industry today are the following: creating a continuous insulating contour on the surface of the facades; elimination of freezing of structures of external walls of facades; creating a favorable indoor climate; reducing building heating costs; selection of optimal design and technological solutions when installing insulation systems; reducing costs for insulation installations; and the execution of facade works in a short time.

A large role in European countries is given to the thermal modernization of buildings. At the same time, special importance is given to the economic component when performing work with thermal insulation. The authors state that the majority of existing Swedish apartment buildings are located in communities covered by district heating. Space heating accounts for the highest percentage of total final energy consumption during the operation phase of these buildings [21]. Therefore, upgrading building envelope elements and replacing low-energy elements can help improve the energy performance of the existing building stock [22].

The problem of energy saving in construction is caused by a significant volume of consumption of fuel and energy resources and the constant increase in tariffs. Increasing the level of thermal protection of building envelopes can significantly reduce heating costs. As the analysis shows, a significant amount of thermal energy is lost in the environment through the building envelope. Depending on the design and height of buildings, these losses amount to 20–60% of the total energy consumption for heating and ventilation [23–25].

Currently, the energy efficiency of buildings occupies a high priority in the construction industry. When designing and operating residential buildings to ensure their energy efficiency by increasing the thermal insulation characteristics of external walls and reducing the costs of heating, ventilation, and air conditioning, optimal engineering solutions should be sought. The possibility of optimizing fence designs from the point of view of reducing heating costs lies in the fact that fences should have maximum thermal protection at minimal cost [26]. Firstly, this is possible through the use of less expensive thermal insulation materials, secondly through the rational choice of their thickness, and thirdly by the selection of a cost-effective design and technological and organizational solutions for thermal insulation of the facades using modeling [27–29].

It is known [13,14,20] that external thermal insulation composite systems finished with plaster with glued and mechanically fastened insulation are most often used in the mass construction of buildings with various structural schemes. This choice of facade insulation technology is due to one of the main reasons for its use—lower price compared with ventilated facades. However, despite the rather long period of their use, due attention is not always paid to the thermal insulation of protruding parts of floors, for example, balconies and bay windows (Figure 1) [30]. This figure clearly shows that the reinforced concrete floor slabs protruding beyond the facade in the form of balconies and bay windows were not insulated at all, which led to significant heat losses. They are “cold bridges” that reduce the energy efficiency of the building, worsen the thermal comfort in the premises, and force their users to spend more money on heating. “Cold bridges” can lead to the appearance of fungi and mold in the corners of rooms and disruption of the microclimate of a room as a whole.



(**a**) (**b**)

Figure 1. A house with insulation: (**a**) a thermogram of a house with bay windows without insulation. (**b**) Ambient air temperature.

The design and development of energy-efficient node connections are also carried out abroad. The experience of German scientists at the Dortmund Passive House Institute (Passiv HausInstitut) indicates that by the European Energy Saving Directive, passive houses are designed by DIN 4108. One solution is to use thermal inserts. According to numerical modeling, with thermal conductivity of walls from 0.13 to 0.21 W/(mK), in the case of using thermal liners with thermal conductivity of less than 0.05 W/(mK), negative values of linear heat transfer coefficients are obtained, as shown in Figure 2 [31].

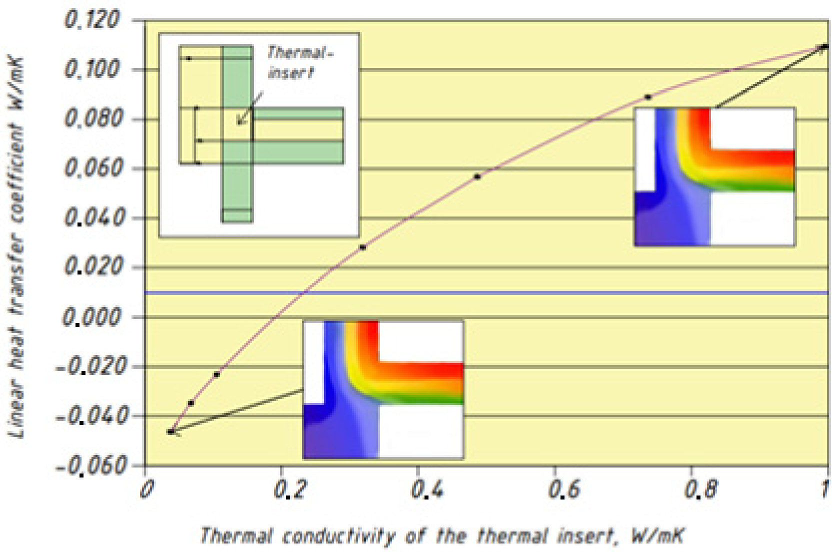


Figure 2. Dependence of the linear heat transfer coefficient of the wall on the thermal conductivity of the thermal liner [31].

The negative values of the linear coefficients shown in Figure 2 show that due to the placement of thermal inserts, the reduced heat transfer resistance can exceed the value of the heat transfer resistance along the main field. From the review, it is clear that nodal connections are among the places with the greatest heat loss of external enclosing structures. To increase the heat transfer value of building envelopes, including in node connections, changes in the thickness and type of insulation are used [7,32–34]. By installing additional insulation, heat transfer resistance and temperature in the inner corner increase [33].

It should be noted that, despite the numerous achievements of scientists in the field of energy efficiency of construction projects, the problem of heat-conducting inclusions remains poorly understood. It is known that almost every building insulated by current codes contains heat-conducting inclusions that disrupt the thermal uniformity of the insulating shell and are a source of significant heat loss. The concept of "heat-conducting inclusion" assumes that this is an element of the enclosing structure, which is located in its volume parallel to the direction of the heat flow and has less thermal resistance than the thermal resistance of the main field by more than 20%. This phenomenon can cause mold and create unfavorable microclimate conditions. Heat-conducting inclusions caused by the design features of the building include interfloor and balcony slabs, columns, pylons, corner connections, etc. [35].

The technology for installing thermal insulation of heat-conducting inclusions is described in detail in the technical specifications for the installation of energy-saving structural units for designers and performers of work on construction sites in France [36]. However, this document does not cover the issue of labor costs for this type of work. The joint efforts of French and Italian scientists in [37] analyzed the economic feasibility of additional thermal insulation for Shoeck Isocorb balconies. Also, the technological sequence of work on the installation of industrially manufactured imported thermal insulation elements is presented in the publications of leading scientists (Umnyakov, Egorov, etc.) of the Research Institute of Building Physics of the Russian Academy of Agricultural Sciences [38,39]. Scientists from the Swiss Polytechnic School (Lausanne) Thomas Keller and Julia de Gastro also present in their work [40] a somewhat different technology for performing work. Victoria Ruth McClung and Hua Ge, experts from the Concordia Technical University of Montreal, Canada, discovered a significant increase in the energy efficiency of a residential building when using thermal insulation blocks [11,41].

This article [42] delves into the analysis of the regression equation, examining the obtained outcomes regarding the influence of individual factors as well as their interactions on the bearing capacity of the element. Subsequently, the second phase involves conducting experimental research using the "Femap V12 with NX Nastran" software for modeling purposes. However, given the fact that the insulation of such places is quite labor-intensive and expensive, many developers, despite the requirements of regulatory documents, are not satisfied with it at all.

During the thermal modernization of buildings, organizational and technological factors play a particularly important role, along with design factors that provide the facility with a given energy efficiency. All of them are united by solutions, the implementation of which will affect the timing of the work. Any problem in managing construction processes is characterized by many solutions. In addition, the constant complication of equipment and technology of construction production and the associated complications of construction and installation work make choosing the optimal solution extremely difficult. Therefore, in construction conditions, construction production models occupy a leading place [43]. The use of various models in the main areas of construction management is a way out of this situation. Modeling is a method for studying various phenomena and processes and developing options for optimal solutions.

Thus, solving the problem of increasing the energy efficiency of buildings by modeling structural, technological, and organizational solutions under given boundary conditions for the installation of adhesive thermal insulation systems for facades is relevant.

2. Materials and Methods

The purpose of this work is to increase the energy efficiency of buildings by choosing effective design, organizational, and technological solutions for external thermal insulation systems for facades finished with plasters.

The working hypothesis is as follows. By using simulation modeling of temperature fields of structural units of facades of complex shape, it is expected to identify possible critical zones of heat loss and areas of formation of cold bridges. This will make it possible to optimize the insulation of protruding parts of facades from the point of view of thermal, economic, and technological efficiency. Optimization consists of developing the optimal insulation area for the building's balcony slabs and, thereby, ensuring the energy efficiency of the building. Based on these decisions and experimental and statistical modeling of organizational and technological factors, it is expected to reduce the duration of construction and installation work on facade insulation.

This research was carried out with wide use of methods of temperature field simulation, methods of optimal planning of experiments, and the use of multifactor mathematical modeling of organizational and technological solutions for insulating external structures of buildings.

Thermal optimization of enclosing structures of complex shapes requires a detailed analysis of the components. This will allow you to identify and avoid freezing areas and determine the location of dew point fronts. Determining these factors using standard external measuring instruments is a complex, time-consuming, and sometimes impossible task. This is especially true for thermal imaging tests, which must be carried out at low external temperatures (1–2 °C) and high temperatures inside the building (at least +16–18 °C) [44].

As the object of research, an 11-storey residential building was adopted with complex-shaped facades, insulated with 50 mm thick mineral wool, and finished with plaster. The building was erected using a frame–stone design. The thickness of the external walls is 640 mm. The walls are made of ceramic bricks. The floors are made of monolithic reinforced concrete. The total area of insulation of the external structures of the building without taking into account optimization problems was 8558 m^2.

The study was carried out in two stages.

In the first stage, the modeling of heat transfer and determination of optimal structural and technological components of thermal insulation were carried out.

To simulate heat transfer, 3D models of the analyzed units were built. The modeling and calculation process was carried out using SolidWorks Simulation Xpress 2021 software [45].

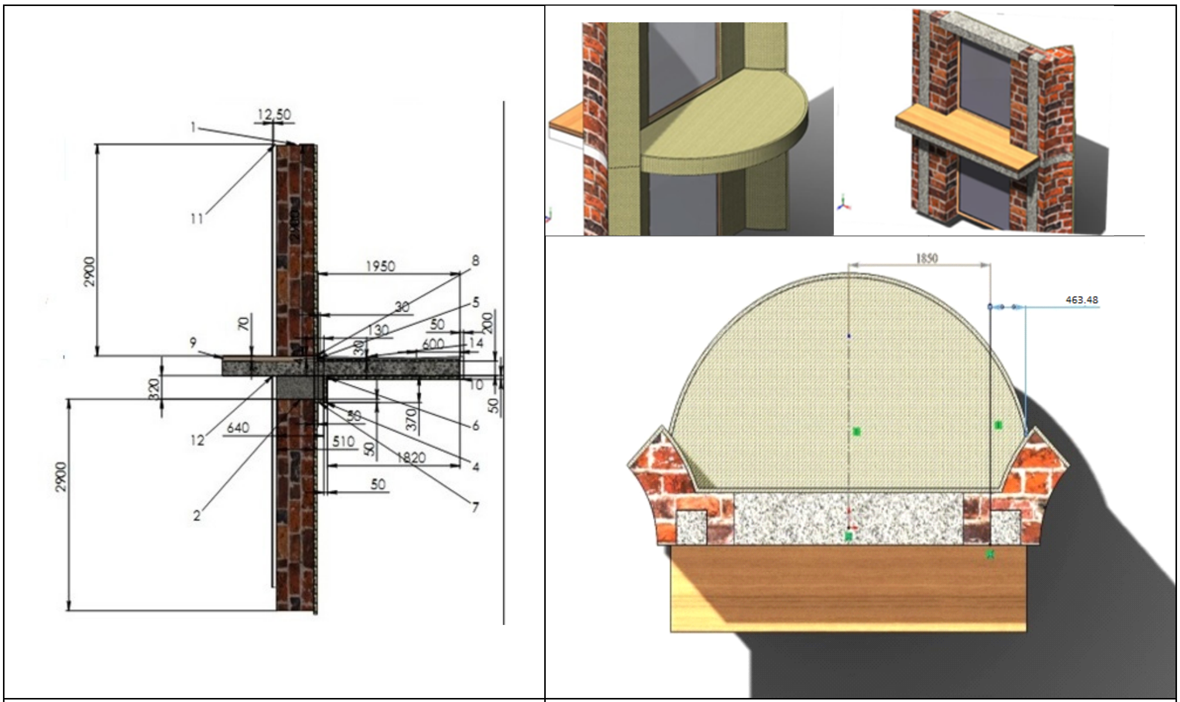
The process of modeling building structures occurs in the following steps:

- Construction of 3D models of individual elements of a building structure and creation of an assembly from various parts necessary for calculations;
- Selection of material parameters for 3D models;
- Selection of thermal loads acting on the 3D model (Table 1);
- Selection of so-called "fixtures" used to "fix" the edges of the model and which should not move during analysis. To prevent analysis failure due to the motion of a stationary body, at least one edge of the part must be constrained. To "fix" the part, two surfaces were chosen: the internal and external surfaces of the part.

Table 1. Parameters for calculation.

Temperature	Minimum	Average	Maximum
Outside air temperature	−18 °C	−16 °C	−12 °C
Indoor temperature	+18 °C	+20 °C	+22 °C

The main task was to analyze cold bridges in monolithic structures of balconies and floor slabs and find ways to eliminate them, as shown in Figure 3.



(a) (b)

Figure 3. Calculation of main node for analysis of temperature fields and heat flows (**a**) and calculation models: (**b**) 1—brick wall 640 mm, 2—reinforced concrete lintel, 3—reinforced concrete monolithic slab, 4—thermal insulating mineral wool slab 250 × 50, 5—thermal insulating mineral wool slab 1250 × 30, 6—thermal insulating mineral wool slab 1200 × 50, 7—heat-insulating mineral wool board 130 × 50, 8—heat-insulating mineral wool board 3000 × 50, 9—cement–sand screed, 10—heat-insulating mineral wool board 280 × 50, 11—air gap, 12—plasterboard, 13—air gap, 14—screed.

When modeling temperature fields and heat flows inside the structures of balcony slabs, the following boundary conditions were accepted:

- The external insulation of the walls and the entire balcony slab is made with a 50 mm thick layer of insulation around the perimeter, as shown in Figure 3a;
- The wall and balcony slabs are not insulated;
- The balcony slab is not insulated, but the wall is insulated;
- The walls and balcony slab are insulated, and the balcony slab's open edge is not insulated;
- There is a difference in the thickness of the insulating layer on the top and bottom of the balcony slab.

The following parameters were used as input data for the simulation:

- Information about the model: all materials that make up the analyzed assembly were included in the analysis, taking into account their placement, as shown in Table 2.
- Physical and mechanical properties of the materials making up the analyzed assembly, including average density, volume, weight, and thermal conductivity, as shown in Table 3.
- Thermal loads, Table 4.

Table 2. Model information.

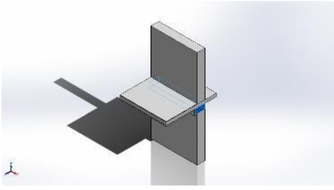
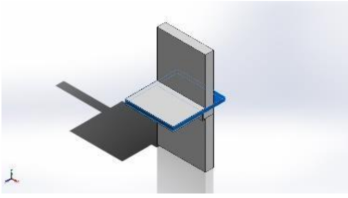
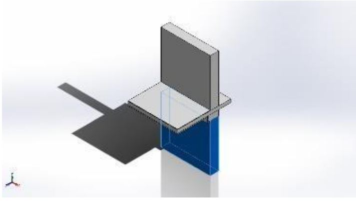
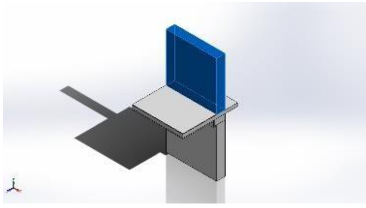
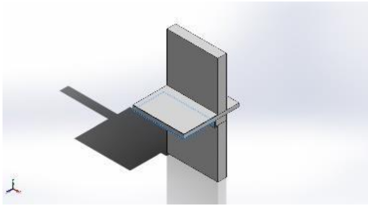
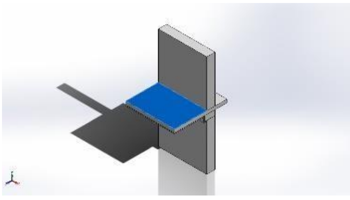
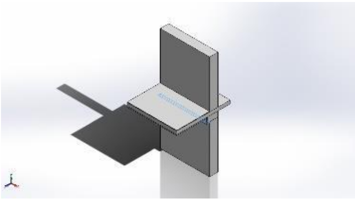
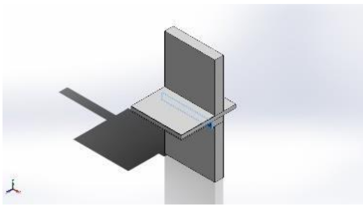
Link to the Model	Viewed as	Volume Properties
	Solid	Weight: 1474.56 kg Volume: 0.6144 m^3 Density: 2400 kg/m^3 Weight: 14,450.7 N
	Solid	Weight: 4680 kg Volume: 1.95 m^3 Density: 2400 kg/m^3 Weight: 45,864 N
	Solid	Weight: 10,648.8 kg Volume: 4.437 m^3 Density: 2400 kg/m^3 Weight: 104,358 N
	Solid	Weight: 10,648.8 kg Volume: 4.437 m^3 Density: 2400 kg/m^3 Weight: 104,358 N
	Solid	Weight: 382.2 kg Volume: 0.273 m^3 Density: 1400 kg/m^3 Weight: 3745.56 N
	Solid	Weight: 432 kg Volume: 0.18 m^3 Density: 2400 kg/m^3 Weight: 4233.6 N
	Solid	Weight: 27.3 kg Volume: 0.0195 m^3 Density: 1400 kg/m^3 Weight: 267.54 N
	Solid	Weight: 133.2 kg Volume: 0.0555 m^3 Density: 2400 kg/m^3 Weight: 1305.36 N

Table 3. Input data for simulation.

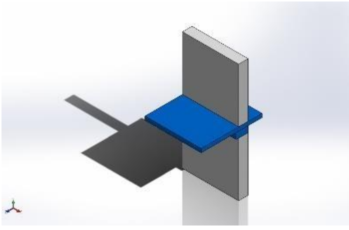
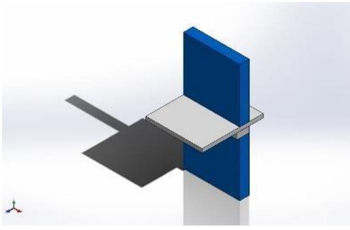
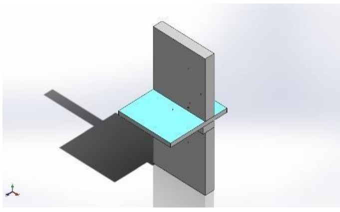
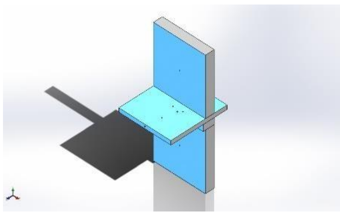
Link to the Model	Properties	Components
 Curve data: N/A	Name: Concrete Model type: Linear Elastic Isotropic Strength criterion: Not defined Thermal conductivity: 1.75 W/(mK) Mass density: 2400 kg/m^3	Slab Lintel
	Name: Brick Model type: Linear Elastic Isotropic Criterion of strength: Not defined Thermal conductivity: 0.58 W/(mK) Average density: 2250 kg/m^3	Wall Wall

Table 4. Input data for simulation.

The Name of the Data	Download Image	Load Data
Convection-1		Objects: 6 faces The convective coefficient is 0.000198375 heat transfer: Cal/(s·cm^2·°C) Time variation: Off Temperature variation: Off Mass temperature Ambient: 18 Celsius
Convection-2		Objects: 7 faces The convective coefficient is 0.000549713 heat transfer: Cal/(s·cm^2·°C) Time variation: Off Temperature variation: OffMass temperature environment: −18 Celsius

In the second stage, using experimental and statistical modeling, the influence of organizational and technological factors on the duration of façade insulation was studied. The planning and implementation of a five-factor experiment was carried out concerning the object of study—an elite residential complex. The total insulation area, taking into account the optimization of the first stage, was 7845.2 m^2.

The experiments were carried out according to a specially synthesized saturated D-optimal plan of the MTP type (mixture, technology, property) [28,46] "triangles on a square", with 15 experimental points and two test points of the plan, as presented in Table 5.

The following were accepted as variable factors:

v_1 = (100 ± 50) %—percentage of use of industrial mountaineering;
v_2 = (100 ± 50) %—percentage of use of construction cradles;
v_3 = (100 ± 50) %—percentage of scaffolding use;
X_4 = (2 ± 1)—number of construction teams for facade work;
X_5 = (5 ± 1)—number of working days per week.

Table 5. The mixture plan matrix "triangles on a square" with responses.

The Numbers of the Points of the Plan	The Levels of Coded Variables					The Value of Natural Variables				
	Interconnected			Technological		Interconnected			Technological	
	v_1	v_2	v_3	X_4	X_5	Industrial Mountaineering	Construction Cradles	Inventory Scaffolding	Brigades, Number	Number of Working Days in Weeks
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
1	1	0	0	-	-	100	-	-	1	4
2	0	1	0	-	-	-	100	-	1	4
3	0	0	1	-	-	-	-	100	1	4
4	0.5	0.5	0	-	0	50	50	-	1	5
5	0	1	0	-	+	-	100	-	1	6
6	0.5	0	0.5	-	+	50	-	50	1	6
7	1	0	0	0	+	100	-	-	2	6
8	0	0	1	0	+	-	-	100	2	6
9	0.5	0	0.5	0	0	50	-	50	2	5
10	2	3	4	5	6	7	8	9	10	11
11	0.33	0.33	0.33	0	+	33.3	33.3	33.3	2	6
12	0	0	1	+	0	-	-	100	3	5
13	0	1	0	+	-	-	100	-	3	4
14	1	0	0	+	-	100	-	-	3	4
15	0	0.5	0.5	+	0	-	50	50	3	5
Checkpoints of the plan										
16	0	1	0	+	+	-	100	-	3	6
17	0.33	0.33	0.333	-	-	33.3	33.3	33.3	1	4

Such schemes make it possible to select the most effective combination of technologies for high-rise construction work with the installation of external adhesive thermal insulation systems on the facade of a building under construction. The legend, Figure 4, should be used to interpret ternary diagrams.

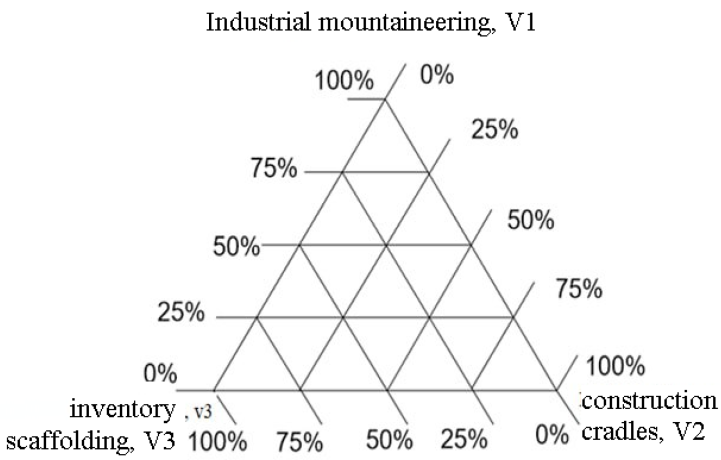


Figure 4. Ternary graph of the combination of means of mechanization of facade insulation in percentage terms.

The distribution of the quality level in the space of technological and organizational factors can be considered as an organizational and technological field with properties in the area Ωx. In our case, the region Ωx is the square of the normalized factors X_4; X_5, where $|Xi| \leq 1$, and the simplices of related variables νi are normalized using standard formulas.

The construction and statistical analysis of experimental statistical models (ESM) was carried out according to standard methods using the interactive program "Compex-2009 v. 1.1", which was developed at the Department of Processes and Apparatuses of the Odesa State Academy of Civil Engineering and Architecture. All models were built with a risk level equal to $\alpha = 0.2$. The model with all significant coefficient estimates was checked for adequacy using the Fisher F criterion. If $Fa < Fcr$ (α, f_{na}, fe), then the model was allowed for further analysis and decision making.

It is only possible to display a graphical representation of the "composition-property" diagram under the influence of two technological factors—$X1$, $X2$—discretely; mixture diagrams $f(v)$ are constructed and analyzed at fixed points of the square $\{x_1, x_2\}$, in particular, at 9 points—the centroids.

Systems whose properties are determined by a group of mixture factors $v = (v_1, \ldots, v_q)T$ and a group of technological factors $x = (x_1, \ldots, x_k)T$ are called [29,46] MTP systems "mixture (M), technology (T), property (P)". The complete vector $K = (q + k)$ of factors in such a system is written as [28]

$$\boldsymbol{u} = (v_T, x_T)^T \tag{1}$$

For the analysis and optimization of "mixture, technology, properties" systems, a complete polynomial of the m-th degree in $\boldsymbol{u}$ (1) cannot be used as a model due to the linear relationship of some factors. Therefore, to describe these systems, multiplication models of the reduced polynomial in x and a polynomial in $\boldsymbol{v}$ or reduced polynomials in $\boldsymbol{u}$ are used.

In particular, for the case $q = 3$ and $k = 2$, the given polynomials have the following form:

$$\begin{gathered} \boldsymbol{Y = A_1v_1 + A_{12}v_1v_2 + b_{14}v_1x_4 + b_{15}v_1x_5 + b_{45}x_4x_5 + b_{44}x_4{}^2} \\ \boldsymbol{A_2v_2 + A_{23}v_2v_3 + b_{24}v_2x_4 + b_{25}v_2x_5 + \cdot + b_{55}x_5{}^2} \\ \boldsymbol{A_3v_3 + A_{13}v_1v_3 + b_{34}v_3x_4 + b_{35}v_3x_5} \end{gathered} \tag{2}$$

In this case, this condition must be met: $\boldsymbol{v_1 + v_2 + v_3 = 1}$. However, these models can be used for decision making only after the algebraic calculation of coefficient estimates is complemented by statistical analysis of both individual coefficients and the model as a whole. Statistical assessment of the effectiveness of an experiment includes assessing the significance of the average values of the results of the experiments of the plan, determining the error of parallel experiments, calculating the dispersion of optimization parameters, checking their homogeneity, and testing statistical hypotheses [30]. Carrying out statistical control makes it possible, with a given degree of probability, to assess the significance of the experimental results and the adequacy of the resulting model to the real process [46].

Checking the adequacy of the model, i.e., verification of its compliance with the real process, is carried out using Fisher's $\boldsymbol{F}$-criterion and depends on the dispersion of the reproducibility of the experiments. Adequacy variance is as follows:

$$\boldsymbol{S^2_{a\partial}} = \sum_{\boldsymbol{i=1}}^{N} \boldsymbol{\Delta Y_i^2 / f_3} \tag{3}$$

$\boldsymbol{F}$-criterion (calculated):

$$\boldsymbol{F_p} = \boldsymbol{S^2_{a\partial} / S^2_y} \tag{4}$$

If the calculated value of the Fisher criterion does not exceed its tabulated value calculated with degrees of freedom $\boldsymbol{f} = \boldsymbol{n} - 1$ and $\boldsymbol{f_3} = \boldsymbol{N} - (\boldsymbol{k} + 1)$ (where $\boldsymbol{k}$ is the number of model coefficients), then the model is considered adequate.

In the next stage, the significance of the model coefficients is checked. If the coefficient is insignificant, i.e., it is less than the experimental error, then such a coefficient can be neglected, and the influence of the factor (or interaction) characterized by it is considered insignificant.

The use of mathematical modeling helps to reduce the time and labor intensity of experimental work and allows scientific research to be carried out at a qualitatively new level.

3. Results

At the first stage of research, as a result of modeling the data array, it was possible to determine the parameters of temperature fields for a given balcony unit (Figure 1a) in frame–stone buildings.

It has been established that a balcony slab without thermal insulation, including walls, exhibits properties in which a cold bridge with subzero temperatures penetrates through the slab into the interior of the room (Figure 5).

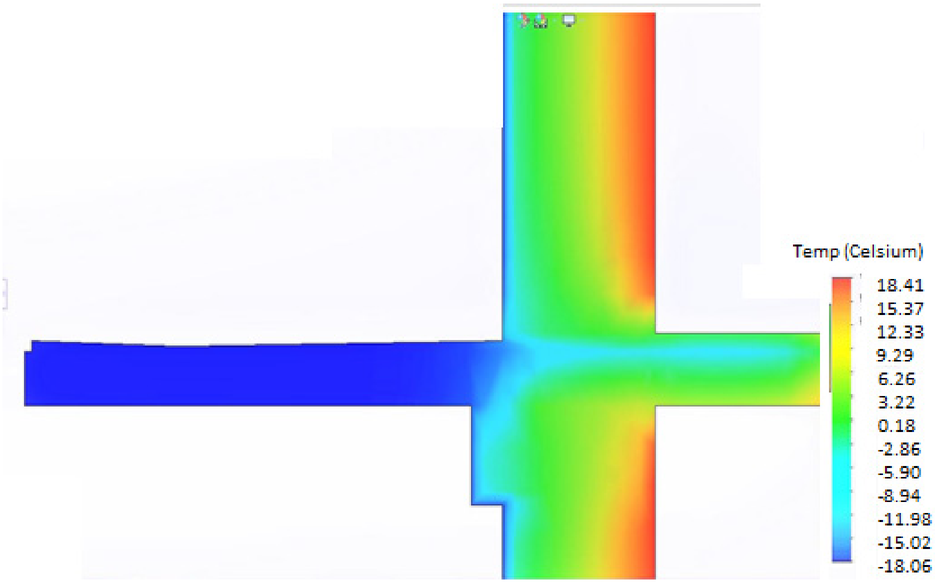


Figure 5. Balcony slab (left) without thermal insulation, including walls: "cold bridge" with negative temperatures (blue color) penetrates the slab and ceiling into the room.

Thus, condensation may form in the internal parts of the room during the cold season at ambient temperatures as low as −18 °C.

Further modeling, in which the balcony slab was insulated along the entire perimeter but without insulation on the open edge of the slab, showed that the cold bridge in the balcony slab with thermal insulation occurs at a considerable distance from the outer wall of the building (Figure 6).

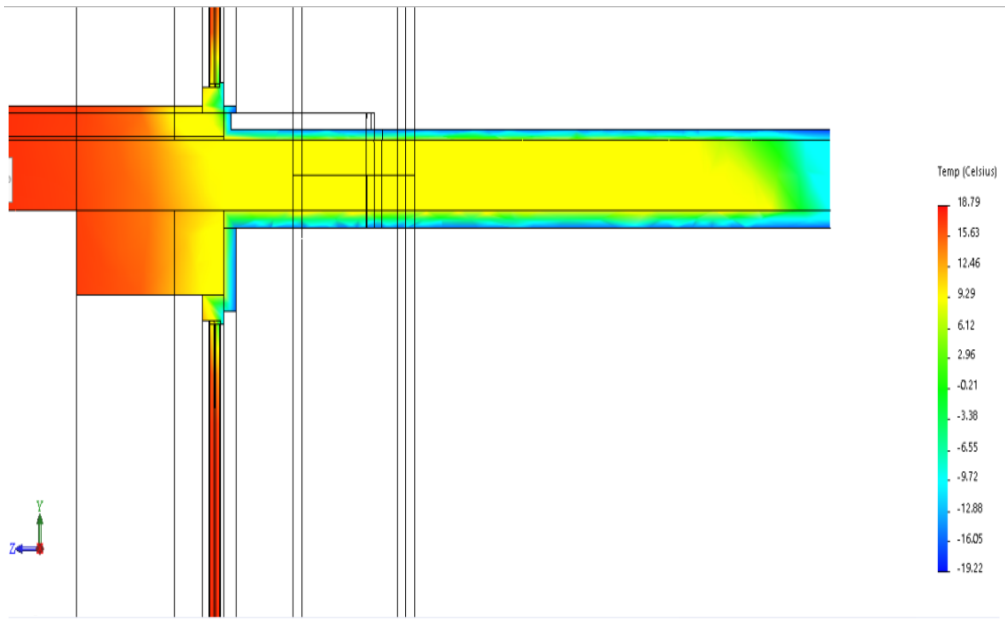
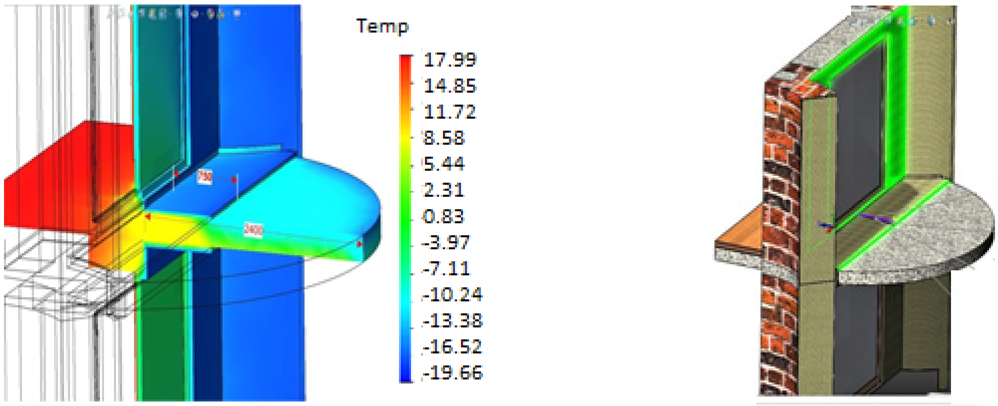


Figure 6. Temperature field inside the slab without end insulation (balcony slab on the right).

Temperature fields were simulated at various distances from the wall with and without end insulation.

The obtained research results and analysis of temperature fields propagating through a monolithic balcony slab made it possible to determine the optimal distance and thickness of the balcony insulation from the building wall. For this particular balcony unit in a frame–brick house, the optimal size of insulation from the outer wall is 750 mm, with a top insulation thickness of 30 mm and a bottom insulation of 50 mm, as shown in Figure 7.



(**a**) (**b**)

Figure 7. Models of insulation of balcony slabs: (**a**) temperature field in the central section of the balcony partially covered with insulation—30 mm from above and 50 mm from below at a distance of 750 mm at an external minimum temperature of −18 °C and +18 °C indoors; (**b**) recommended coating of balcony insulation.

This insulation will prevent cold bridges from moving into the interior and thus eliminate the occurrence of mold, mildew, and other problems in critical areas. This insulation technology is relevant for modern multistory buildings with nonstandard volumetric and architectural solutions, which are built using frame–brick, frame–monolithic, or monolithic schemes without thermal breaks between the balcony slab and the monolithic floor slab, with open balconies, bay windows, or open loggias. As a result of optimization, while ensuring the specified quality parameters (excluding freezing of the balcony slab into the room), the insulation area of the balconies was 712.8 m^2 instead of the designed 2210 m^2.

In the next stage, the experimental statistical modeling of organizational and technological factors was carried out. The duration of work on insulating the external structures of the building was taken as an indicator.

As stated earlier, the balcony slab must be completely insulated along the entire perimeter for heat loss reduction, following the requirements of regulatory documents. However, the modeling results of the previous stage made it possible to select the optimal insulation parameters for the balcony slab. At the same time, the influence of the above optimization of insulation of balcony slabs on reducing the external structure's insulation volume was taken into account.

When interpreting the modeling results, the principles of technical and economic efficiency of construction and installation work were taken into account. The criteria used in the study using experimental statistical modeling, based on which the results will be proposed and interpreted, include minimizing the duration of installation of facade insulation and balconies with stucco finishes.

Let us consider diagrams of the "triangles on a square" type.

As shown by the calculation results performed in the Compex program, the relative deviation of DELT is on average 0.002, which causes a small experimental error N_e = 1.7737. This, in turn, requires conducting research with sufficiently high measurement accuracy.

As a result of the experimental statistical modeling in the factor space Ω_x, a model was obtained, Y_{req} (5) (T_{se} = 2.918), describing the influence of organizational factors, such as the number of working days per week (X_4) and the number of brigades (X_5), as well as the degree of combination of mechanisms for carrying out high-rise work (v_1, v_2, v_3)

on the duration of construction—installation work for external structures insulation of a residential building.

$$\begin{aligned} Y_{req} = &+168.3v_1 \pm 0v_1v_2 - 112.6v_1x_4 - 42.44v_1x_5 + 54.2x_4{}^2 + 25.3x_4x_5 \\ &+161.5v_2 \pm 0v_1v_3 - 111.01v_2x_4 - 43{,}613v_2x_5 + 13.08x_5{}^2 \\ &+175.69v_3 \pm 0v_2v_3 - 114.603v_3x_4 - 46{,}406v_3x_5 \end{aligned} \quad (5)$$

The nature of the influence of factors is indicated by the signs of the coefficients. The "+" sign indicates that with increasing factor value the response magnitude increases, and with the "−" sign, it decreases.

The graphical response with isolines of the multivariate Y_{req} model is presented in Figure 8.

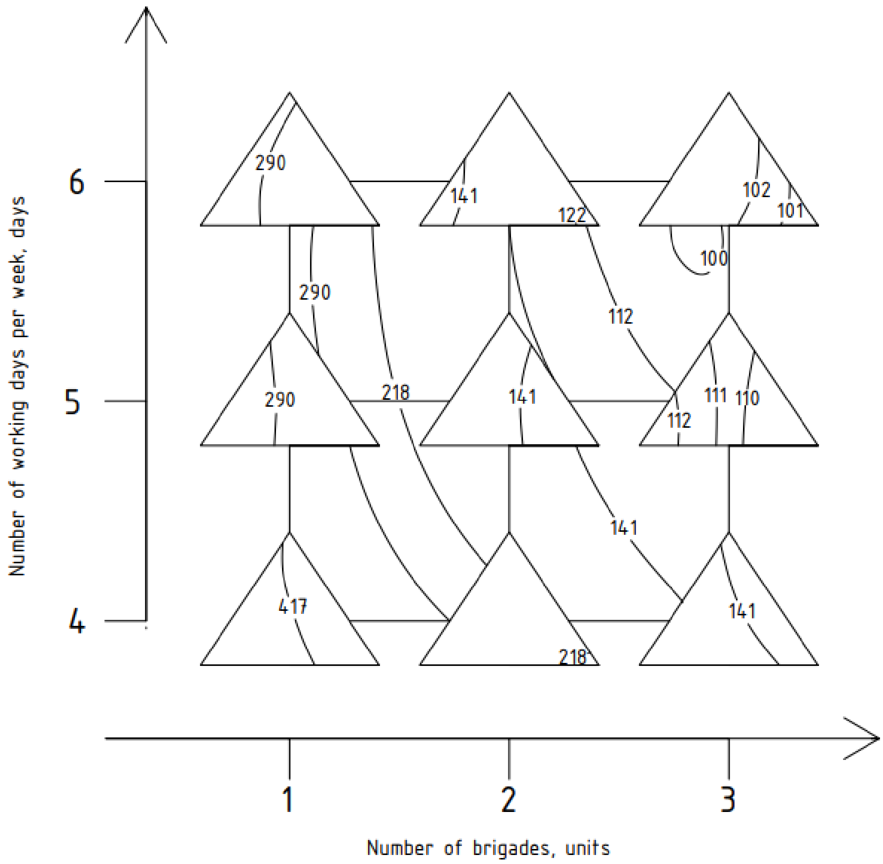


Figure 8. The influence of organizational and technological factors on the duration of the project for insulating facades using the "wet" method.

In this diagram, the duration function for performing facade work with insulation of the external structures of a building reaches extrema at the following points:

$Y_{req\ min}$ = 91 days. at (v_1 = 0; v_2 = 1; v_3 = 0; X_4 = +1; X_5 = +1);

$Y_{req\ max}$ = 430 days. at (v_1 = 0; v_2 = 0; v_3 = 1; X_4 = −1; X_5 = −1).

The duration of insulation of an elite residential building is the amount of calendar time from the beginning of the first task to the completion of the last task, taking into account the accepted technological and organizational schemes for performing the work.

Analyzing the graphical representation of Model 1, the following can be observed (Figure 8). The nature of the influence of technological factors on the studied indicator changes depending on the degree of combination of work (as it decreases, the duration of isolation increases).

To achieve the minimum values of the indicator "Duration of work" $Y_{req\ min}$, it is recommended to use a technological scheme using construction cradles. Unlike scaffolding and industrial climbing systems, it provides greater management flexibility, allowing the maximum combination of tasks that is not possible with scaffolding technology. Using the industrial mountaineering method increases the duration of insulation work, which leads to additional costs for construction and installation work. Thus, the desired result in terms of "Duration of work" is achieved when using construction cradles. The minimum duration of the external structure's insulation of the building is achieved with 100% use of cradles when the work is organized within 6 working days by three brigades. It should be noted that, as mentioned earlier, each team consists of 25 workers of different specialties. In addition, ES modeling showed the possibility of using 70 people instead of 75. The value of the "Duration of work" indicator, in this case, will be 91 days.

4. Discussion

The scientific work shows that the tasks of efficient energy consumption of buildings and structures have remained key for many decades. Therefore, the efforts of the world's leading engineering centers (ASHRAE, ISO, ABOK, etc.) are aimed at developing and modernizing codes for energy-efficient buildings. An energy research (energy modeling) tool is a model of the thermal regime of buildings and structures, which allows for a feasibility study of an energy management system following ISO 50001:2018 "Energy management systems—Requirements with guidance for use" [47]. The thermal model of the building must ensure maximum accuracy of calculations. Among the factors influencing the adequacy of the model, the following can be identified: detailing of the models of enclosing structures, properties of all materials that are given in the nodal solution, and weather conditions—the influence of temperature loads depending on the time of year, etc. The constructed thermal model takes into account the specifics of the building associated with features of possible heat gains and heat losses, as well as features of heat exchange of internal and external surfaces of enclosing structures with air through a heat-conducting inclusion. The program stipulates that the model is based on the heat balance equation of the room, which takes into account all possible heat losses and heat gains, subject to the boundary conditions. The parameters of thermal processes are set according to the reference and regulatory literature. These include the heat capacity of walls and ceilings, the heat transfer coefficients of enclosing structures, and the relationship of characteristics with outside air temperature. The results of the simulation modeling of the thermal regime of buildings with alternating ambient temperatures show that the distribution of heat flows inside the balcony floor slab is influenced by the following factors: temperature, the distance of the laid insulation from the outer wall, the insulation of the surface of the floor slab from above and below, the physical and mechanical properties of the insulation, and its thickness. Based on heat flow modeling, a structural and technological solution for the junction of the balcony slab to the outer wall has been developed. This ensures optimal insulation areas of the horizontal surface of the slab.

Thus, presented study gives two novel scientific results. First is substantiated constructive and technological solutions for insulating complex-shaped facade elements during the design stage. This result is practically oriented, improves current normative document and has technical novelty. The second results is novel experimental statistical model of façade insulation duration allows numerical management of technological and organizational regimes of this works in changing economic and commercial environment.

The above study made it possible to reduce the insulation area of all balconies and terraces by 50%, which affected the total volume of insulation of the entire building while maintaining the building's energy efficiency indicators.

In turn, with the help of experimental statistical modeling of organizational and technological solutions for facade thermal insulation, the calculation of the minimum terms for insulating the facade of the building under study was carried out.

The research results were implemented during the thermal modernization of both the building under study, built using a frame–stone scheme, and buildings created using a frame–monolithic scheme in Odesa, Ukraine (Figure 9).

(**a**) (**b**)

Figure 9. Installation of insulation of balcony floor slabs in accordance with research results at facilities in the city of Odesa: (**a**) loggia, (**b**) balcony.

In the future, at ambient temperatures favorable for thermal imaging control, observations will be carried out to confirm the correctness of the adopted design and technological solutions. At the moment, there have been no critical comments from management companies or building residents.

5. Conclusions

1. The modeling of insulation in the modern software product SolidWorks Simulation Xpress 2021 allows, at the design stage, the selection of cost-effective designs and technological solutions for insulating the facade elements of complex shapes.

2. It has been determined that the most effective way is not to insulate the entire balcony slab, as required by regulatory documentation, but rather insulating a 750 mm wide section of the outer wall is sufficient. In this case, the thickness of the insulation on top of the slab is 30 mm, and on the bottom of the slab, it is 50 mm.

3. This insulation technology is economically feasible for modern multistory buildings with nonstandard volumetric architectural solutions, built using frame–stone, frame–monolithic, or monolithic schemes without thermal breaks between the balcony slab and the monolithic floor slab, characterized by the presence of a large volume of open-type balconies and bay windows or not-closed loggias.

4. It is recommended to use a technological scheme using scaffolding to achieve the minimum time for insulation work. The work is to be carried out within 6 working days with the participation of three brigades. Experimental statistical modeling showed the possibility of employing 70 people instead of 75, resulting in a project duration of 91 days.

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