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Correlation model for cost and technical characteristics of thermal insulation material used in enclosing structure

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Abstract. Research relevance is determined by the need for development of the effective design and organizational-technological solutions at the stage of design or renovation of housing construction objects in the conditions of tightening requirements for the duration, cost, and quality of construction projects being implemented, as well as the limitations of scientific developments used for determination of the characteristics for the above-mentioned solutions in terms of the completeness of the factors under consideration and the objectivity of taking into account the relationships between them. Problem statement: The paper considers a design solution formed in relation to the enclosing structure within housing construction object, which involves the use of thermal insulation material as a separate layer of the structure. It is necessary to form mathematical description of the relationships between the technical and cost characteristics of the thermal insulation material and the energy and economic efficiency indicators of the design solution. Research aim: development of tools to determine the characteristics of design solutions formed in relation to the enclosing structure within housing construction object, based on energy and economic efficiency criteria. Research tasks are the following: review and comparative analysis of scientific developments in the field of determination of characteristics for design solutions formed in relation to enclosing structures within housing construction objects; development of analytical model describing correlation between the specific cost and technical characteristics of thermal insulation material used as a separate layer of the enclosing structure; implementation of the model on a practical example; formation of recommendations for the use of the model during solution of the problems related to determination of characteristics of design solutions for enclosing structures. Results. The analytical model has been developed that describes the linear dependence of the specific cost of thermal insulation material used in the enclosing structure on its technical characteristics. The results of the implementation of the analytical model on a practical example confirmed its high practical significance. Findings. The developed analytical model can be used for predictive calculation of the specific cost of thermal insulation material corresponding to the mineral wool on the basis of the specified values for its technical characteristics. Due to the composition of the factors taken into account, the developed analytical model can be effectively integrated into the structure of tools for determination of the characteristics for design solutions related to enclosing structures within housing construction object on the basis of energy and economic efficiency criteria.

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1. Introduction

In the modern conditions of the construction industry's upgrowth, characterized by tightening of requirements for the duration, cost, and quality of construction projects, the issues of rational justification of design and organizational-technological solutions (formed at the stage of design or renovation of housing construction objects) with taking into account energy and economic efficiency indicators, gain particular importance. At the same time, the above-mentioned indicators are generally significantly influenced by the characteristics of enclosing structures within construction objects. Nevertheless, the results of the preliminary analysis of scientific developments related to the formation of design solutions for enclosing structures have shown the limitations of the applied tools in terms of objectively taking into account the relationships between the characteristics of design solutions in terms of the technologies and materials used and the corresponding indicators of energy and economic efficiency. At the same time, the problem of mathematical description of the above-mentioned relationships is aggravated by the presence of a wide variety of applied building materials and technologies. The above circumstances determined the feasibility of conduction of the research aimed at the development of tools for determination of the characteristics for design solutions formed in relation to the enclosing structure as part of housing construction object on the basis of energy and economic efficiency criteria.

The object of the research is a design solution formed in relation to the enclosing structure as part of housing construction object, which involves the use of thermal insulation material as a separate layer in the structure.

The subject of the research is the relationship between the characteristics of the thermal insulation material within the enclosing structure and the indicators connected to the energy and economic efficiency of the corresponding design solution.

At the initial stages of the research, the review and comparative analysis of scientific developments in the field of determination of the characteristics for design solutions formed in relation to enclosing structures within construction objects has been conducted. Based on the results of the mentioned-above review and analysis, the following conclusions have been made:

1. Scientific developments related to the subject area under consideration are classified according to the following main features:
   - category of scientific results: methodological developments [1–4]; instrumental developments [5–37];
   - category of instrumental developments: models and methods based on analytical calculation [5–19]; models and methods involving the implementation of optimization procedures [20–37];
   - research area: analysis of the relationships between the characteristics of design solutions for enclosing structures within housing construction objects and the corresponding energy efficiency indicators on the basis of experimental and statistical studies [1–4]; determination of the characteristics related to the temperature and thermal conditions for enclosing structures within housing construction objects [5–12]; determination of energy [13–15] and economic [16–19] efficiency indicators for design solutions connected to enclosing structures within housing construction projects; determination of characteristics for design solutions connected to enclosing structures within housing construction projects on the basis of energy and economic efficiency criteria [20–37];
   - category of computational algorithms used: stochastic swarm intelligence algorithms [20, 25, 29, 35]; stochastic evolutionary algorithms [23, 27, 29–33, 36, 37]; deterministic integer convex optimization algorithms [26].
2. The overwhelming majority of scientific developments have relatively low practical significance due to the following features:
   - significant dependence of the results obtained on the volume and quality of the initial experimental or statistical data [1–4, 24, 28];
   - lack of description for principles related to the developments' application during the procedures of comparative analysis of various design solutions for enclosing structures [5, 6, 8, 10, 12];
   - high labor intensity of the calculation process's implementation due to the need for experimental justification of individual formula components for each alternative variant of conditions related to the technological process of construction [7, 9, 11];
   - lack of consideration of the influence of the building materials' structure characteristics on the calculated values of energy efficiency indicators [12–15];
   - lack of direct consideration of changes over time in the construction object's operational characteristics on the calculated values of economic efficiency indicators [16, 17];
   - lack of consideration of the influence of design solutions' characteristics on the corresponding indicators of economic efficiency [21];

- impossibility of objective assessment of the development's practical significance due to absence of description of its implementation process on practical example, as well as obtained results [22];
- significant reduction of the area of admissible combinations of values for characteristics of the design solution during implementation of sequential analytical calculation [16, 17, 34];
- presence of a large number of binary unknown variables and indirect constraints associated with them, which causes relatively low convergence rate for the computational algorithm [20, 23, 25–27, 29, 31–33, 35–37];
- relatively high labor intensity of the calculation process, implementation due to necessity of creation of artificial neural network, its training and verification of obtained results [27, 29, 30, 33, 36, 37];
- relatively high labor intensity of the calculation process's implementation due to complex structure of mathematical expressions in the absence of appropriate software tools for automation of calculations [34].

Thus, based on the obtained results of the review of scientific developments, the conclusion has been made about insufficiency of the level of scientific elaboration of the issues related to the determination of the characteristics for design solutions formed in relation to enclosing structures within construction. The mentioned-above results also determined the formulation of following research objectives:

1. Development of the analytical model of the correlation between the specific cost and technical characteristics of thermal insulation material used in the enclosing structure.
2. Implementation of the developed model on a practical example.
3. Formulation of recommendations for the use of the developed model during the solution of the problems related to determination of the characteristics for design solutions connected to enclosing structures within housing construction objects.

2. *Materials and Methods*

The main provisions based on which the analytical model has been developed include the following:

1. The object of consideration is thermal insulation material used as a separate layer in the external enclosing structure of a housing construction project.
2. The specific – per unit area of the structure's surface – cost of thermal insulation material is determined by its technical characteristics, for which specific numerical values are known for various options (manufacturers and models) of the material. The recommended composition of technical characteristics determining the specific cost of thermal insulation material is presented in Table 1.
3. There is a functional dependence of the specific cost of thermal insulation material – dependent category – on the values of its technical characteristics (hereinafter referred to as the functional dependence).
4. The functional dependence is linear with respect to the following components (factors): the inversed value of the thermal conductivity coefficient; the ratio of other technical characteristics of the material to the thermal conductivity coefficient. The composition of the analytical model's factors corresponding to the recommended composition of the technical characteristics of the thermal insulation material is presented in Table 1.
5. The analytical model of the functional dependence (hereinafter referred to as the analytical model) is determined by an expression of the form:

$$\tilde{y} = \beta_0 + \sum_{j=1}^{n} \beta_j \cdot \theta_j, \tag{1}$$

where $\tilde{y}$ – predicted value of the unit cost of acquisition of thermal heat-insulating material (value of the dependent category), CU/m^2; n – number of factors taken into account in the analytical model, units; θ_j – factor value with index $j\left(j = 1, 2, \ldots, n\right)$, $MU_{\theta j}$; for more information, see Table 1; β_j – analytical model parameter is the coefficient of proportionality of the value of the dependent category to the value of the factor with the index $j\left(j = 1, 2, \ldots, n\right)$, (CU/(m$^2\cdot$ $MU_{\theta j}$); β_0 – an additional parameter of the analytical model is the constant of the unit cost for the material, CU/m^2.

Table 1. Description of the parameters of the thermal insulation material and the corresponding factors of the analytical model.

Index	Name of the technical characteristic for the thermal insulation material	Measure unit	Symbol	Name of the factor of the analytical model	Measure unit	Designation
1	2	3	4	5	6	7
j	–	$MU_{\chi j}$	χ_j	–	$MU_{\theta j}$	θ_j
1	Thermal conductivity coefficient	$\frac{W}{m \cdot °C}$	λ	Inversed value of thermal conductivity coefficient	$\frac{m \cdot °C}{W}$	$1/\lambda$
2	Thickness	m	δ	Ratio of the thickness to the thermal conductivity coefficient	$\frac{m^2 \cdot °C}{W}$	δ/λ
3	Average density to the thermal conductivity coefficient	$\frac{kg}{m^3}$	ρ	Ratio of average density to the thermal conductivity coefficient	$\frac{kg \cdot °C}{m^2 \cdot W}$	ρ/λ
4	Water absorption in 24 hours (by volume)	%	ν	Ratio of the water absorption in 24 hours (by volume) to the thermal conductivity coefficient	$\frac{\% \cdot m \cdot °C}{W}$	ν/λ
5	Flammability group index (1)	-	φ	Ratio of the flammability group index to the thermal conductivity coefficient	$\frac{m \cdot °C}{W}$	φ/λ
6	Vapor permeability coefficient	$\frac{mg}{m \cdot h \cdot Pa}$	μ	Ratio of the vapor permeability coefficient to the thermal conductivity coefficient	$\frac{mg \cdot °C}{h \cdot Pa \cdot W}$	μ/λ

Note: (1) The parameter of the thermal heat-insulating material has the following alternative values: 1 – non-flammable material, 2 – flammability group “G3”; 3 – flammability group “G4”.

6. It is advisable to determine the parameters of the analytical model by implementation of the procedure related to the formation of a multifactorial linear regression model on the basis of statistical data containing information about the set of variants (models) of thermal insulation material in terms of the technical characteristics’ values specified in Table 1 (converted into the values of the factors connected to the analytical model), as well as the specific cost of the material; the formation of the mentioned-above statistical data is generally carried out without taking into account the operating conditions of a specific enclosing structure.
7. To assess the adequacy of the analytical model, it is advisable to use the coefficient of determination.

The initial data necessary for the formation of an analytical model include the names, values of technical characteristics and unit cost of thermal insulation material for each variant as part of a preliminary prepared sample, as well as data necessary to assess the adequacy of the formed analytical model.

A detailed description of the initial data used in the processes of forming an analytical model and assessing its adequacy is presented in Table 2.

Table 2. Source data used during the processes related to the formation of the analytical model and assessment of its adequacy.

No.	Name of the source data element	Measure unit	Designation/ Expression
1	2	3	4
1	**Indexes**		
1.1	Index of the thermal insulation material’s technical characteristic (factor of the analytical model) (1)	-	$j = 1, 2, \ldots, n$
1.2	The value of the index for the technical characteristic of the thermal insulation material (factor of the analytical model) corresponding to the thermal conductivity coefficient	-	$j_\lambda \in \{1, 2, \ldots, n\}$
1.3	Index of the analytical model’s parameter (1)	-	$k = 0, 1, 2, \ldots, n$
1.4	Index of the thermal insulation material’s variant (model) (2)	-	$l = 1, 2, \ldots, g$

No.	Name of the source data element	Measure unit	Designation/ Expression
1	2	3	4
2	**Source data used for the formation of an analytical model**		
2.1	General source data		
2.1.1	Number of parameters of thermal heat-insulating material	units	n
2.1.2	Number of thermal heat-insulating material instances	units	g
2.2	Input data specified for each individual instance of thermal heat-insulating material with an index l ($l=1,2,...,g$)		
2.2.1	Name of the copy of the thermal insulation material	-	-
2.2.2	Actual value of specific cost for the thermal insulation material	CU/m^2	y_l
2.3	Initial data specified for each individual variant of thermal insulation material with an index l ($l=1,2,...,g$) and each individual technical characteristic with index j ($j=1,2,...,n$)		
2.3.1	Thermal insulation material's technical characteristic value	CU/(m$^2\cdot$ $MU_{\chi j}$)(3)	χ_{lj}
3	**Initial data used for the formed analytical model's adequacy assessment**		
3.1	General source data		
3.1.1	Minimum permissive value of the coefficient of determination	-	R^{2min}

Note: (1) the upper value of the index is determined by the input data element in item 2.1.1 of the table; (2) the upper value of the index is determined by the source data element in item 2.1.2 of the table; (3) the designation "$MU_{\chi j}$" defines the measure unit for the thermal insulation material's technical characteristic with the index j (see Table 1).

Detailed description of the calculated characteristics enumerated during the processes related to the formation of the analytical model and assessment of its adequacy is presented in Table 3.

Table 3. Calculated characteristics calculated as part of the process of forming an analytical model and assessing its adequacy.

No	Name of the calculated characteristic	Measure unit	Expression
1	2	3	4
1	**Calculated characteristics enumerated during the formation of the analytical model**		
1.1	Characteristics calculated for each individual variant of thermal insulation material with index l ($l=1,2,...,g$) and each factor of the analytical model with the index j ($j=1,2,...,n$)		
1.1.1	Factor value	$UM_{\theta j}$ (1)	$\theta_{lj}=\begin{cases}\frac{1}{\chi_{lj}}, \text{if } j=j_\lambda;\\ \frac{\chi_{lj}}{\chi_{lj=j_\lambda}}, \text{ else}\end{cases}$
1.2	General calculated characteristics		
1.2.1	An element of the main matrix of a system of equations located at the intersection of a row with an index r ($r=0,1,2,...,n$) and a column with an index c ($c=0,1,2,...,n$)	–	$\mathrm{B}_{rc}=\begin{cases} g, \text{ if } r=0, c=0;\\ \sum_{l=1}^{g}\chi_{lj=r}, \text{ if } r\ge 1, c=0;\\ \sum_{l=1}^{g}\chi_{lj=c}, \text{ if } r=0, c\ge 0;\\ \sum_{l=1}^{g}\chi_{lj=r}\cdot\chi_{lj=c}, \text{ else}\end{cases}$
1.2.2	Main matrix of the system of equations	–	$\mathrm{B}=\{\mathrm{B}_{rc}\}$

No	Name of the calculated characteristic		Measure unit	Expression
1	2		3	4
1.3	Characteristics calculated for each individual parameter of the analytical model with an index k ($k = 0,1,2,...,n$)			
1.3.1	A member of a partial matrix of a system of equations that is at the intersection of a row with an index r ($r = 0,1,2,...,n$) and a column with an index c ($c = 0,1,2,...,n$)		–	$\mathrm{B}_{rc}^{k} = \begin{cases} \sum_{l=1}^{g} y_l, \text{ if } r = 0, c = k; \\ \sum_{l=1}^{g} y_l \cdot \chi_{lj=k'}, \text{ if } r \geq 1, c = k; \\ \mathrm{B}_{rc}, \text{ else}; \end{cases}$
1.3.2	Partial matrix of a system of equations		–	$\mathrm{B}_k = \left\{ \mathrm{B}_{rc}^{k} \right\}$
1.3.3	Analytical model parameter's value [(2)]		diff. [(3)]	$\beta_k = \frac{\lvert \mathrm{B}_k \rvert}{\lvert \mathrm{B} \rvert}$
2	**Calculated characteristics enumerated during the assessment of the adequacy for the analytical model**			
2.1	Characteristics calculated for each individual variant of thermal insulation material with index l ($l = 1,2,...,g$)			
2.1.1	Predicted value of the material's the specific cost		CU/m²	$\tilde{y}_l = \beta_{k=0} + \sum_{k=1}^{n} \beta_k \cdot \theta_{lj=k}$
2.2	Aggregated calculated characteristics			
2.2.1	Absolute deviation of the predicted value of the unit value from the actual value	minimal	CU/m²	$\Delta^{\min} = \min_{l} \left\{ \lvert \tilde{y}_l - y_l \rvert \right\}$
2.2.2		average	CU/m²	$\Delta^{aver} = \frac{1}{g} \cdot \sum_{l=1}^{g} \lvert \tilde{y}_l - y_l \rvert$
2.2.3		maximal	CU/m²	$\Delta^{max} = \max_{l} \left\{ \lvert \tilde{y}_l - y_l \rvert \right\}$
2.2.4	Relative deviation of the predicted value of the unit cost from the actual value	minimal	–	$\sigma^{min} = \min_{l} \left\{ \frac{\lvert \tilde{y}_l - y_l \rvert}{y_l} \right\}$
2.2.5		average	–	$\sigma^{aver} = \frac{1}{g} \cdot \sum_{l=1}^{g} \frac{\lvert \tilde{y}_l - y_l \rvert}{y_l}$
2.2.6		maximal	–	$\sigma^{max} = \max_{l} \left\{ \frac{\lvert \tilde{y}_l - y_l \rvert}{y_l} \right\}$
2.2.7	Calculated coefficient of determination		–	$R^2 = 1 - \frac{\sum_{l=1}^{m} \left(\tilde{y}_l - y_l \right)^2}{\sum_{l=1}^{m} \left(y_l - \frac{\sum_{l=1}^{g} y_l}{m} \right)^2}$

Note: (1) the notation "$MU_{\theta\,j}$" defines the measure unit for the analytical model's factor with an index j (see Table 1); (2) the designation $|...|$ in mathematical expression of the calculated characteristic corresponds to the calculation result for the determinant of the corresponding matrix argument; (3) in the case $k = 0$ the measure unit of the design characteristic corresponds to "CU/m²"; otherwise "CU/(m²· $MU_{\theta\,j=k}$)".

The adequacy of the analytical model is assessed on the basis of a condition determined by the expression:

$$R^2 \geq R^{2\,min}. \tag{2}$$

The description of the components for expression (2) is presented in item 3.1.1 of Table 2 and item 2.2.4 of Table 3.

3. Results and Discussion

The proposed analytical model has been implemented on a practical example to solve the problem related to the formation of the dependence of the specific cost for thermal insulation material based on mineral wool, expanded polystyrene foam and extruded polystyrene foam on the corresponding technical characteristics. The initial data for the implementation of the model included information on 100 material variants available on the Russian building materials market in the period from February 2019 to March 2022 – the values of the specific cost and technical characteristics of the material specified in Table 1, with the exception of the vapor permeability coefficient, for which there was no data in the documentation for the material variants (the effect of the vapor permeability coefficient on the specific cost has been assumed to be negligible). The values of the source data elements are given in columns 1–8 of Table 4. Minimum permissible value of the coefficient of determination $\left(R^{2\,min}\right)$ has been assumed to be 0.9. 1 CU has been taken equal to 1 ruble ($0.011687 as of July 29, 2024)

The results of the model implementation in numerical form are presented in Table 5 (including the calculated values of the model parameters and the coefficient of determination) and in column 9 of Table 4 (predicted values of the unit cost of acquisition of various material samples), in graphical form – in Fig. 1 (deviations of the predicted values of the unit cost from the actual values in the context of individual material samples).

According to the results obtained, the average absolute deviation of the predicted value of the unit cost of a material sample from the actual value $\left(\Delta^{\text{aver}}\right)$ is 17.492 CU/m^2, and the corresponding relative $\left(\sigma^{\text{aver}}\right)$ is about 12.4%, while the estimated value of the coefficient of determination $\left(R^2\right)$ is approximately 0.909, exceeding the above-mentioned minimum permissible value.

It is important to note that the proposed analytical model, in comparison with the predictive models presented in [18, 20], is characterized by a similar or slightly lower adequacy (the determination coefficient R^2 for the model presented in [18] is 0.922, for the basic and modified models described in [20] – 0.903 and 0.927, respectively). However, unlike the above-described developments, the proposed analytical model can be effectively used as a basis for creation and implementation of an optimization model for determination of the technical characteristics for thermal insulation material within enclosing structures as part of a housing construction object, since it ensures the direct calculation of optimal values for the material's technical characteristics directly based on the results of the optimization model's implementation without using additional predictive models, for which certain requirements for adequacy indicators must be ensured.

Thus, based on the results obtained, the conclusion was made about high practical importance of the developed analytical model related to the dependence of the unit cost of thermal heat-insulating material on its technical characteristics.

Table 4. Values of technical and cost characteristics of the samples of heat-insulating material used in the process of implementing the analytical model.

Index	Name of the sample of thermal heat-insulating material	The value of the thermal insulation material's technical characteristic with the index (j)					Specific cost	
		1	2	3	4	5	Actual	Predicted
1	2	3	4	5	6	7	8	9
l	-	$\chi_{lj=1}$	$\chi_{lj=2}$	$\chi_{lj=3}$	$\chi_{lj=4}$	$\chi_{lj=5}$	y_l	$\tilde{y}_l$
-	-	$\frac{W}{(m\cdot°C)}$	m	kg/m³	%	–	$\frac{CU}{m^2}$	$\frac{CU}{m^2}$
1	ISOVER Warm House Twin, 5490×1220×50 mm	0.041	0.05	11	1	1	55	57.72
2	URSA Geo M-11, 7000×1200×50 mm	0.04	0.05	11	1	1	57	57.05
3	URSA Universal, 1250×600×50 mm	0.036	0.05	16	1	1	58	63.30
4	URSA Geo Light, 6250×1200×50 mm	0.044	0.05	11	1	1	58	59.53
5	USSR Geo P-15, 1250×610×50 mm	0.037	0.05	15	1	1	60	62.06
6	KNAUF ECOROLL, 1000×610×50 mm	0.04	0.05	12	1	1	61	58.72
7	KNAUF ECOROLL Rulon, 6800×610×50 mm	0.039	0.05	10.5	1	1	61	55.50
8	ISOVER Classic Plus, 1200×610×50 mm	0.038	0.05	15	1	1	62	62.65
9	ISOVER Warm House Slab, 1170×610×50 mm	0.038	0.05	13.5	1	1	62	60.01
10	ISOVER Profi, 6000×1220×50 mm	0.04	0.05	14	1	1	63	62.06
11	ROCKWOOL Econom, 1000×600×50 mm	0.039	0.05	26	1	1	63	82.04
12	URSA Terra, 1250×610×50 mm	0.036	0.05	16	1	1	64	63.30
13	KNAUF ECOROLL Slab, 1230×610×50 mm	0.04	0.05	12.5	1	1	65	59.56
14	KNAUF ECOROLL Extra Slab, 1230×1220×50 mm	0.037	0.05	11	1	1	66	54.84
15	KNAUF ECOROLL Thermal Cooker, 1230×610×50 mm	0.04	0.05	12.5	1	1	67	59.56
16	ISOVER Warm Walls Strong, 1000×610×50 mm	0.034	0.05	20.5	1	1	72	70.90
17	ISOVER Frame P37, 1170×610×50 mm	0.037	0.05	15	1	1	76	62.06
18	EKOVER Lite 30, 1000×600×50 mm	0.037	0.05	30	2.5	1	77.8	97.18
19	PAROC eXtra Light, 1200×600×50 mm	0.038	0.05	25	1	1	78	80.22
20	ISOROC UltraLite, 1000×600×50 mm	0.038	0.05	33	1.5	1	83	96.89
21	EKOVER Lite Universal, 1000×600×50 mm	0.037	0.05	28	2.5	1	83.5	93.57
22	ISOVER Classic, 6150×1220×50 mm	0.041	0.05	11	1	1	84	57.72
23	URSA PureOne 37RN, 6250×1200×50 mm	0.037	0.05	15	1	1	84	62.06
24	ISOVER Warm walls, 1170×610×50 mm	0.036	0.05	20	2	1	85	76.23
25	TECHNONICOL Rocklight 1200×600×50 mm	0.04	0.05	35	2	1	85	102.08

Index	Name of the sample of thermal heat-insulating material	The value of the thermal insulation material's technical characteristic with the index (*j*)					Specific cost	
		1	2	3	4	5	Actual	Predicted
1	2	3	4	5	6	7	8	9
26	ECOVER Light 35, 1000×600×50 mm	0.035	0.05	35	2	1	86.15	104.62
27	PENOPLEX Osnova, 1200×600×20 mm	0.03	0.02	30	0.4	3	92	154.62
28	ISOVER Warm House Roll, 7000×1220×50 mm	0.038	0.05	17	1	1	93	66.16
29	ISOROC Isolite L, 1000×600×50 mm	0.038	0.05	50	1	1	94	124.15
30	PAROC eXtra, 600×1200×50 mm	0.036	0.05	30.5	1	1	95	90.19
31	TECHNONICOL GreenGuard Universal, 1200×600×50 mm	0.035	0.05	37.5	1	1	96	103.72
32	KNAUF TeploKnauf Nord 1230×610×50 mm	0.035	0.05	20.7	1	1	97	71.66
33	ROCKWOOL Light Butts Scandic, 800×600×50 mm	0.036	0.05	32	1	1	98	92.98
34	PAROC eXtra Smart, 1200×600×50 mm	0.036	0.05	32	1	1	100	92.98
35	ROCKWOOL Light Butts, 1000×600×50 mm	0.036	0.05	37	1	1	108	102.25
36	PENOPLEX Comfort, 1200×600×20 mm	0.03	0.02	30	0.4	3	110	154.62
37	URSA Geo M-11, 7000×1200×100 mm	0.04	0.1	11	1	1	113	136.83
38	URSA PureOne 34PN, 1250×600×50 mm	0.034	0.05	20	1	1	113	69.92
39	Master Therm PSB-S-15, 1200×1000×50 mm	0.043	0.05	12.5	4	2	115	121.23
40	BASWOOL Standard 60, 1200×600×50 mm	0.038	0.05	60	1	1	116	141.72
41	TECHNONICOL Technoblock Standard 1200×600×50 mm	0.035	0.05	45	1.5	1	117	120.86
42	URSA Geo P-15, 1250×610×100 mm	0.037	0.1	15	1	1	119	148.30
43	ISOVER Warm House Slab, 1170×610×100 mm	0.038	0.1	13.5	1	1	123	143.98
44	URSA Universal, 1250×600×100 mm	0.036	0.1	16	1	1	123	151.93
45	ISOROC Isolight Lux, 1000×600×50 mm	0.038	0.05	60	1.5	1	125	144.34
46	ROCKWOOL Econom, 1000×600×100 mm	0.039	0.1	26	1	1	126	163.86
47	URSA Terra, 1250×610×100 mm	0.036	0.1	16	1	1	126	151.93
48	ISOVER Classic Plus, 1170×610×100 mm	0.037	0.1	15	1	1	128	148.30
49	BASWOOL Standard 70, 1200×600×50 mm	0.038	0.05	70	1	1	129	159.30
50	KNAUF ECOROLL Slab, 1230×610×100 mm	0.04	0.1	12.5	1	1	131	139.33

Index	Name of the sample of thermal heat-insulating material	The value of the thermal insulation material's technical characteristic with the index (*j*)					Specific cost	
		1	2	3	4	5	Actual	Predicted
1	2	3	4	5	6	7	8	9
51	KNAUF ECOROLL Extra Slab, 1230×610×100 mm	0.037	0.1	10.5	1	1	133	140.18
52	ISOVER Profi, 5000×1220×100 mm	0.037	0.1	14	1	1	134	146.50
53	PENOPLEX Basis, 1200×600×30 mm	0.03	0.03	30	0.4	3	138	175.90
54	Master Therm PSB-S-25, 1200×1000×50 mm	0.041	0.05	20.05	3	2	146	130.49
55	ECOVER Lite Station Wagon, 1000×600×100 mm	0.037	0.1	28	2.5	1	152.1	179.81
56	ISOVER Warm walls, 1170×610×100 mm	0.036	0.1	20	1	1	160	159.35
57	PAROC eXtra Light, 1200×600×100 mm	0.038	0.1	25	1	1	162	164.19
58	ISOROC Ultralite L, 1000×600×100 mm	0.038	0.1	33	1.5	1	165	180.86
59	URSA PureOne 37RN, 10000×1200×100 mm	0.037	0.1	15	1	1	166	148.30
60	PENOPLEX Comfort, 1200×600×30 mm	0.03	0.03	30	0.4	3	167.5	175.90
61	ROCKWOOL Cavity Butts, 50 mm	0.035	0.05	45	1	1	169	118.03
62	TECHNONICOL Rocklight 1200×600×100 mm	0.04	0.1	35	2	1	170	181.85
63	TECHNONICOL Technovent Standard, 1200×600×50 mm	0.034	0.05	80	1.5	1	176	190.68
64	PENOPLEX Osnova, 1200×600×40 mm	0.03	0.04	30	0.4	3	184	197.17
65	ISOROC Isolite L, 1000×600×100 mm	0.038	0.1	40	1.5	1	188	193.16
66	TECHNONICOL GreenGuard Universal, 1200×600×100 mm	0.035	0.1	37.5	1	1	191	194.89
67	ROCKWOOL Lite Butts Scandic XL, 1200×600×100 mm	0.036	0.1	37	1	1	192.5	190.89
68	ISOROC IsoLite, 1000×600×100 mm	0.038	0.1	50	1	1	193	208.12
69	EKOVER Lite 45, 1000×600×100 mm	0.035	0.1	45	1.5	1	195.8	212.03
70	ROCKWOOL Lite Butts Scandic, 800×600×100 mm	0.036	0.1	37	1	1	196.5	190.89
71	PAROC eXtra, 600×1200×100 mm	0.04	0.1	30.5	1	1	196.5	169.38
72	PAROC eXtra Smart, 1200×600×100 mm	0.036	0.1	32	1	1	200	181.61
73	BASWOOL Standard 50, 1200×600×100 mm	0.038	0.1	50	1	1	207	208.12
74	ROCKWOOL Venti Butts, 1000×600×50 mm	0.035	0.05	90	1	1	207.5	203.88
75	PENOPLEX Comfort, 1200×600×40 mm	0.03	0.04	30	0.4	3	217	197.17

Index	Name of the sample of thermal heat-insulating material	The value of the thermal insulation material's technical characteristic with the index (*j*)					Specific cost	
		1	2	3	4	5	Actual	Predicted
1	2	3	4	5	6	7	8	9
76	TECHNONICOL Technovent Optima, 1200×600×50 mm	0.036	0.05	90	1.5	1	217	203.32
77	ROCKWOOL Lite Butts, 1000×600×100 mm	0.036	0.1	37	1	1	218	190.89
78	BASWOOL Facade 110, 1200×600×50 mm	0.038	0.05	110	1	1	218	229.59
79	Master Therm PSB-S-15, 1200×1000×100 mm	0.043	0.1	12.5	4	2	229	195.44
80	BASWOOL Standard 60, 1200×600×100 mm	0.038	0.1	60	1	1	231	225.70
81	PENOPLEX Osnova, 1200×600×50 mm	0.03	0.05	30	0.4	3	232	218.44
82	TECHNONICOL Technoblock Standard 1200×600×100 mm	0.035	0.1	45	1.5	1	234	212.03
83	TECHNONICOL Technoroof N Extra 600×1200×50 mm	0.037	0.05	100	1.5	1	234	218.15
84	BASWOOL Facade 120, 1200×600×50 mm	0.038	0.05	120	1	1	236	247.16
85	ECLOSE Ecofacade Standard, 1000×600×50 mm	0.036	0.05	100	1.5	1	238.5	221.87
86	EKOVER Ecofacade Optima, 1000×600×50 mm	0.035	0.05	95	1.5	1	241	216.26
87	BASWOOL Facade 140, 1200×600×50 mm	0.038	0.05	140	1	1	246	282.31
88	ISOROC IsoLite Luxe,1000×600×100 mm	0.038	0.1	60	1.5	1	251	228.31
89	PAROC Linio 15 600×1200×50 mm	0.039	0.05	108	1	1	252	222.44
90	BASWOOL Standard 70, 1200×600×100 mm	0.038	0.1	70	1	1	257	243.27
91	ISOVER Plaster facade, 1200×600×50 mm	0.038	0.05	100	1	1	260	212.02
92	ISOROC Isofas 140, 1000×500×50 mm	0.035	0.05	140	1.5	1	262	302.11
93	PENOPLEX Comfort, 1200×600×50 mm	0.03	0.05	30	0.4	3	263	218.44
94	PENOPLEX Osnova, 1200×600×60 mm	0.03	0.06	30	0.4	3	276	239.72
95	PENOPLEX Comfort, 1200×600×60 mm	0.03	0.06	30	0.4	3	277	239.72
96	TECHNONICOL Technofas Optima, 600×1200×50 mm	0.039	0.05	120	1	1	281	242.99
97	ROCKWOOL Rockfasade, 1000×600×50 mm	0.037	0.05	150	1	1	285.5	305.71
98	ISOROC Isophas 160, 1000×500×50 mm	0.039	0.05	160	1	1	293	311.48
99	ROCKWOOL Butts Facade, 1000×600×50 mm	0.037	0.05	130	1.5	1	318	272.29
100	TECHNONICOL Technoroof Extra 600×1200×40 mm	0.037	0.04	180	1.5	1	340	345.28

Table 5. Values of the calculated characteristics obtained during implementation of the analytical model on a practical example.

No	Name of the calculated characteristic		Measure unit	Designation	Value
1	2		3	4	5
1	The value of the model parameter corresponding to the factor	inversed value of thermal conductivity coefficient	$\beta_{k=1}$	$MU_{\theta\ j=1}$	–7.197
2		ratio of the thickness to the thermal conductivity coefficient	$\beta_{k=2}$	$MU_{\theta\ j=2}$	63.819
3		ratio of average density to the thermal conductivity coefficient	$\beta_{k=3}$	$MU_{\theta\ j=3}$	0.067
4		ratio of the water absorption in 24 hours (by volume) to the thermal conductivity coefficient	$\beta_{k=4}$	$MU_{\theta\ j=4}$	0.198
5		ratio of the flammability group index to the thermal conductivity coefficient	$\beta_{k=5}$	$MU_{\theta\ j=5}$	1.982
6	The constant of the unit cost for the material (additional parameter of the model)		$\beta_{k=0}$	CU/m²	84.318
7	Absolute deviation of the predicted value of the unit value from the actual value	minimal	Δ^{min}	CU/m²	0.052
8		average	Δ^{aver}	CU/m²	17.492
9		maximal	Δ^{max}	CU/m²	62.625
10	Relative deviation of the predicted value of the unit cost from the actual value	minimal	σ^{min}	-	0.001
11		average	σ^{aver}	-	0.124
12		maximal	σ^{max}	-	0.681
13	Calculated coefficient of determination		R^2	-	0.909

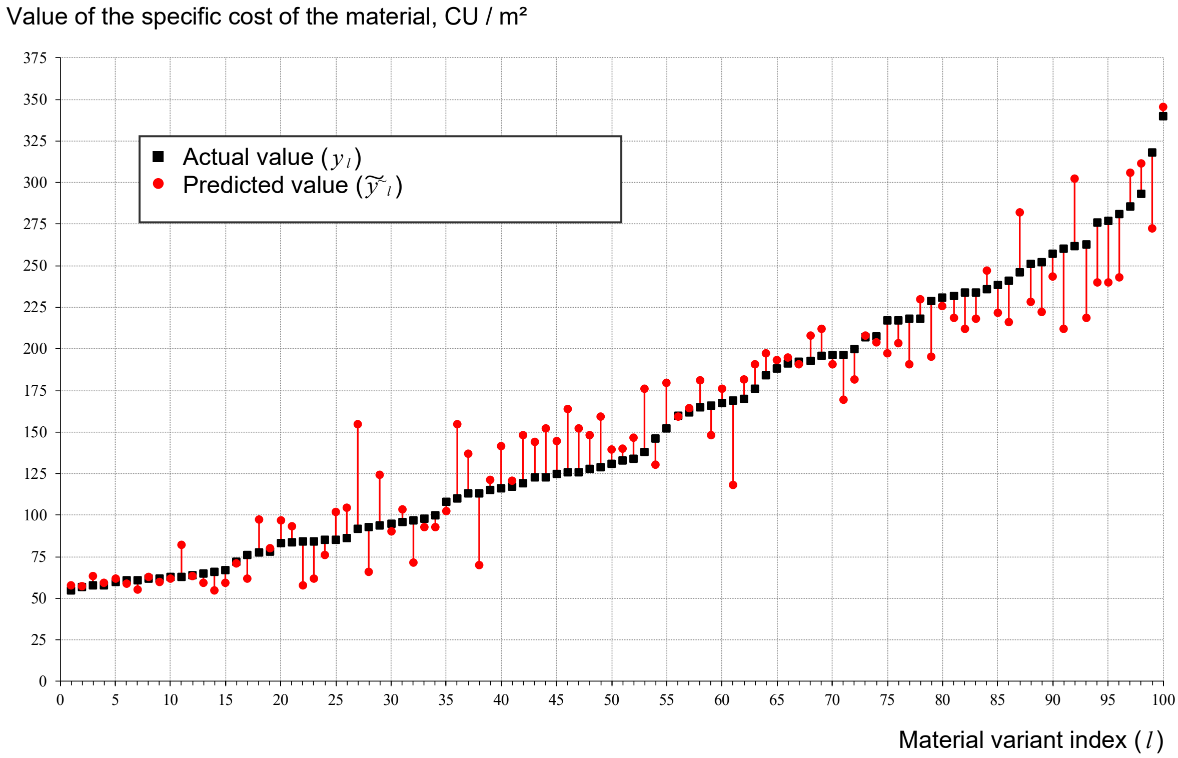

Figure 1. Deviations of the predicted values of the unit cost from the actual values in the context of individual variants of thermal insulation material.

Also, at the final stages of the research, the following recommendations have been formed in relation to the use of the developed analytical model during the solution of the problems related to determination of the characteristics for design solutions connected to enclosing structures within housing construction objects:

1. It is advisable to use the developed analytical model as a component of the mathematical description of energy efficiency indicators for design solutions formed in relation to enclosing structures; in particular, the mathematical expression for the simple payback period for a design solution corresponding to a housing construction object at the renovation stage will have the form

$$T = \frac{\left(\beta_0+\beta_{j=1}\cdot\frac{1}{\lambda}+\beta_{j=2}\cdot\frac{\delta}{\lambda}+\beta_{j=3}\cdot\frac{\rho}{\lambda}+\beta_{j=4}\cdot\frac{\nu}{\lambda}+\beta_{j=5}\cdot\frac{\varphi}{\lambda}+\beta_{j=6}\cdot\frac{\mu}{\lambda}+y_{\text{mnt}}\right)\cdot k_{\text{nrg}}}{\left(\frac{1}{\sum\limits_{s\in S_0}\frac{\delta_s}{\lambda_s}}-\frac{1}{\sum\limits_{s\in S_0}\frac{\delta_s}{\lambda_s}+\frac{\delta}{\lambda}}\right)\cdot c_{\text{he}}\cdot D_{\text{d}}\cdot k_{\text{exp}}} = f\left(\frac{1}{\lambda},\frac{\delta}{\lambda},\frac{\rho}{\lambda},\frac{\nu}{\lambda},\frac{\varphi}{\lambda},\frac{\mu}{\lambda}\right), \quad (3)$$

where T – payback period of the design solution, years; y_{mnt} – specific cost of the thermal insulation material's installation, CU./m^2; k_{nrg} – energy units' conversion factor, W·h/Gcal; s – index of the enclosing structure's layer; S_0 – set of indexes of structural layers that are not related to thermal insulation material; δ_s – thickness of the material related to the layer with index s within the structure, m; λ_s – thermal conductivity coefficient of the material related to the layer with index s within the structure, W/(m·°C); c_{he} – specific cost of thermal energy, CU/Gcal; D_{d} – heating period's temperature-time indicator, °C·day; k_{exp} – conversion factor for time measure units, h/day.; the description of the other components of expression (3) is presented in Table 1.

2. It is advisable to use the factors included in the analytical model as components of the mathematical description of energy efficiency indicators for the mentioned-above design solutions; in particular:

   – the expression for the enclosing structure's thermal resistance will have the form

$$R = \sum_{s\in S_0}\frac{\delta_s}{\lambda_s}+\frac{\delta}{\lambda} = f\left(\frac{\delta}{\lambda}\right), \quad (4)$$

where R – enclosing structure's thermal resistance, m^2·°C/W;

   – the expression for the enclosing structure's vapor permeability resistance (in the case where the thermal insulation material is located between the inner surface of the structure and the corresponding plane of maximum moisture) will have the form

$$R_\mu = \sum_{s\in S_\mu}\frac{\gamma_s\cdot\delta_s}{\mu_s}+\frac{\gamma\cdot\delta}{\mu} = f\left(\frac{\delta}{\lambda},\frac{\mu}{\lambda}\right), \quad (5)$$

where R_μ – enclosing structure's vapor permeability resistance, m²·h·Pa/mg; S_μ – set of indexes of structural layers that are not relates to thermal insulation material and located within the space between the inner surface of the structure and the corresponding plane of maximum moisture; γ, γ_s – the share of the thickness of the heat-insulating material and other material related to the layer with the index s in the structure (respectively) within the space between the inner surface of the structure and the corresponding plane of maximum moisture; μ_s – vapor permeability coefficient of the material r to the layer with index s within the structure, mg/(m·h·Pa).

3. The mentioned-above results of the mathematical description of the energy and economic efficiency indicators for design solutions should be used as a basis for creation of the tools for determination of the values for the analytical model factors (see column 4 of Table 1) as characteristics of design solutions formed in relation to enclosing structures within housing construction objects:
   - analytical models – systems of algebraic or transcendental equations – by establishing a correspondence between the calculated and required (specified in the regulatory documentation) values of the energy and economic efficiency indicators for design solutions, taking into account acceptable discrepancies;
   - optimization models – by using individual energy and economic efficiency indicators for design solutions criteria associated with target functions, and the remaining indicators – as criteria associated with constraints with the use of the required (specified in the regulatory documentation) values of the indicators.

It is important to note that the quadratic (relative to the factors of the developed analytical model) structure of expression (3), as well as the structure of expressions (4) and (5), which can be reduced to linear (relative to the factors of the developed analytical model), will ensure the possibility of using standard (available in modern software environments for mathematical modeling) computational algorithms for the implementation of the mentioned-above tools.

4. Conclusions

During the research the following results have been obtained:

1. Review and analysis of scientific developments in the field of determination of the characteristics for design solutions formed in relation to enclosing structures in housing construction objects has been conducted. Based on the results of the of the mentioned-above review and analysis, the conclusion has been made about the limitations of existing tools connected to the taking into account the relationships between the characteristics of design solutions in terms of the technologies and materials used and the corresponding indicators of energy and economic efficiency.
2. An analytical model of the correlation between the specific cost and technical characteristics of thermal insulation material has been developed. The model assumes a linear dependence of the specific (per unit of surface area of the structure) cost of insulation on the inverse value of the thermal conductivity coefficient of the material, as well as on the ratios of the material’s other technical characteristics to the mentioned-above coefficient.
3. The developed analytical model has been implemented using a practical example. The results of formation of the model on the basis of a set of thermal insulation material’s variants – in particular, the value of the determination coefficient – has shown that the developed tool has high practical significance.
4. Recommendations for the use of the developed analytical model during the solution of the problems related to determination of the characteristics for design solutions connected to enclosing structures within housing construction objects have been formulated.

On the basis of the results obtained during the research, the following conclusions have been made:

1. The developed analytical model can be used for predictive calculation of the specific cost of thermal insulation material based on mineral wool with the use of the specified values of the material’s technical characteristics.
2. Due to the composition of the factors taken into account, the developed analytical model can be effectively integrated into the structure of tools for determination of the characteristics for design solutions formed in relation to enclosing structures within housing construction objects on the basis of energy and economic efficiency criteria.

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