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Thermoeconomic model of a building's thermal protection envelope and heating system

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Abstract. The article is devoted to the determination of the patterns of joint influence exerted by the heating system and heat-protective envelope of a building on its energy consumption, taking into account the composition of the enclosing structures and the peculiarities of the course of thermodynamic processes in the enclosing structures and engineering equipment. The paper presents an overview of the literature on energy saving in the field of construction. It is concluded that it is necessary to form a new approach to optimizing the thermal insulation of buildings based on the method of thermoeconomics, which allows increasing the energy efficiency of buildings. A schematic diagram of the object under study is presented, for which a thermoeconomic model has been developed in the form of several zones connected in series. All cost components affecting the energy efficiency of buildings have been investigated, and the division of costs into energy and non-energy costs is substantiated. Dependences of the reduced costs on the variables to be optimized are given. The dependence of the reduced costs on the cost of the chosen enclosing structures (heat-shielding shell) of the building and engineering equipment is revealed. The analysis of the results obtained is carried out. It is concluded that it is possible to decrease the reduced costs by an average of 20–25 % in comparison with traditional approaches, and the energy consumption of the building by 30–34 %.

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1. Introduction

In recent decades, the issues of energy saving in the field of construction are extremely relevant in all countries. According to various estimates, only in the field of housing and communal services, the potential resources of energy saving are at least 50 %. In the Russian Federation, resolutions of the Government of the Russian Federation have been adopted, which formulate a program for improving energy efficiency in the field of construction. In accordance with this program, the energy consumption of buildings should be systematically reduced. For example, in the period 2016–2020 by 30 %, and after 2021 by 40 %.

The decisive influence on the energy consumption of the building is exerted by the heat-protective envelope of the building, which is a set of enclosing structures that form a closed loop that limits the heated volume of the building.

Therefore, at present, it is necessary to develop existing and find new approaches to optimizing the heat-shielding envelope of buildings in order to increase the energy efficiency of buildings under construction and reconstruction. The relevance of these issues is confirmed by the regular scientific conferences and seminars on this topic.

One of the tasks in this direction is the optimization of interacting and interconnected heat fluxes in a complex architectural-constructive (thermodynamic) system with a variety of its constituent elements of the building envelope (heat shield) and engineering equipment, each of which is an energy carrier and an energy transmitter. A fundamental feature of this system is the fact that a building as a single energy system is not a simple summation of these elements, but a special combination of them, which gives the entire system as a whole new qualities that are absent in each of the elements.

The fundamentals of a systematic approach to a building as a single energy system, the theoretical foundations of the creation of energy efficiency buildings are set forth in the works of Yu.A. Tabunshchikova, for example [1].The energy saving indicator is understood as a qualitative and / or quantitative characteristic of projected or implemented energy saving measures. Activities in the field of energy conservation of buildings under construction and renovation are characterized by indicators of actual energy savings, reduction of losses of energy resources, including by optimizing the operating parameters of energy consumption, carrying out energy-saving measures that do not require significant investments, etc.

There is a fairly large number of different works, approaches, methods for assessing the energy consumption of buildings, which allow taking into account all the main types of energy costs and their reduction through the use of almost any known energy-saving measures.

It should be noted the importance of having a well-developed regulatory framework in the field of thermal protection of buildings. The issues of regulation of energy efficiency in construction, measures to reduce energy consumption of buildings are considered in the work [2].The work notes that it is most expedient to increase energy efficiency by combining various design and engineering measures, for example, simultaneously increasing the heat-shielding properties of enclosing structures and using modern engineering energy-saving methods. The development of the regulatory framework in the field of thermal protection of buildings is also influenced by the existing differences in Russian and international standards in determining the calculated values of thermal conductivity of building materials and products. In work [3], it is indicated that the calculated and actual values of the thermal conductivity of building materials used in the construction of external enclosing structures are inconsistent, which leads to an increase in heat loss through them and the loss of thermal energy for heating buildings. The article also notes that a significant revision of the standards on the basis of which building materials are manufactured is required, and their correct representation in the current regulatory documents.

The problem of measuring thermal performance during the acceptance of buildings into operation, as well as when performing work on the energy classification of buildings during operation is solved in work [4]. The authors propose a two-stage procedure for determining the specific consumption of heat energy for heating: The authors propose a two-stage procedure for determining the specific consumption of heat energy for heating:

The effectiveness of LEED certification in terms of reducing the energy consumption of buildings, the feasibility of using available energy performance indicators for buildings certified according to the LEED standard, are discussed in [5]. An archetype-based quantification of uncertainties in the thermal building model (energy consumption model) is carried out in the work [6].

The features of comparing the economic efficiency of various energy saving measures based on a mathematical model for assessing the discounted payback period of investments aimed at reducing the energy resources consumed in the building are considered in the work [7].

In work [8], on the basis of experimental data, two methods of facade insulation are analysed: a ventilated facade system and an external thermal insulation composite system, an assessment of the energy saving potential and the discounted payback period of investments for facade insulation is given.

A dynamic numerical model of thermal protection of enclosing structures based on heat balance equations is proposed by the authors of the article [9]. A simplified dynamic model was developed and implemented in Python 2.7, the authors compared the values of energy demand for heating and air conditioning with advanced software systems: EnergyPlus, BEPS and TRNSYS.

The effect of thermal insulation thickness in building envelope on carbon dioxide emissions is discussed in [10]. The work [11] considers the problem of calculating the optimal thermal protection of buildings using the theory of risk. The function of the density distribution of damage has been determined, which makes it possible to determine the acceptable damage and the corresponding thickness of thermal protection, minimizing the probability of damage release beyond a given level.

The problem of taking into account the influence of heat-conducting inclusions on the reduction of resistance to heat transfer during the thermal modernization of panel buildings is considered in work [12]. The studies took into account such heat-conducting inclusions as the design of panel joints, the slope of the window and the geometry of the outer wall (outer corner). Possible ways to improve the heat-shielding properties of wall panels are considered.

The study of thermal inertia in the heat-protective envelope of buildings was carried out in works [13, 14].These works indicate that taking into account thermal inertia makes it possible to obtain optimal solutions for the heat-protective envelope of buildings, allowing to reduce the energy consumption of the building.

There is a fairly large number of scientific works in which, in order to increase energy efficiency, the features of the flow of heat and mass transfer processes in the enclosing structures, the features of the functioning of engineering systems are investigated [15–17].

Book [18] describes the optimal design and modernization of energy efficient buildings. The book contains energy statistics, building codes for energy efficiency, and standards from around the world. It also provides an overview of advanced building energy efficiency technologies, including dynamic insulation materials, phase change materials, LED lighting and daylight controls, and more. Applied solutions for energy efficient modernization of buildings with a description of materials, technologies are given in the book [19].

The integration (embedding) of photovoltaic cells into a building envelope, such as a façade or roof, to generate energy from sunlight to reduce the building's energy consumption is presented in the article in [20]. Also, an economic analysis was carried out and the advantages of introducing the proposed system over traditional facades and roofing building materials were shown.

The possibilities of using artificial intelligence in the design of energy efficient buildings, forecasting and minimizing energy consumption, and developing strategies to reduce environmental and climate impacts are discussed in [21]. This article provides an overview of recent AI applications in energy efficient buildings, with a focus on machine learning and large databases. Directions for future research are also indicated. It is emphasized that artificial intelligence can significantly improve the energy efficiency and economic efficiency of buildings that are designed to provide residents with a comfortable living environment.

In most of the above works, an economic calculation of the effectiveness of energy-saving measures is carried out, based on the minimization of the reduced costs for the creation and operation of the building envelope. The main differences in these works are in the methods and formulas for calculating the reduced costs.

Modern research shows that energy systems, which include a complex system consisting of elements of a building's heat-shielding envelope and engineering equipment, should be evaluated using thermodynamic analysis methods. Accordingly, the function of the reduced costs should take into account not only the complex composition of the enclosing structures, but also the peculiarities of the course of thermodynamic processes in the enclosing structures and engineering equipment.

From the methods of thermodynamic analysis, exergy analysis is increasingly used [22, 23]. An increase in the number of studies based on exergy analysis is evidenced by the fact that an International Conference on Exergoeconomics was planned in August 2020 [24]. Thermoeconomics as a mechanism for comparing technical systems is a unique combination of thermodynamic (exergy) and cost analyzes and is capable of providing a designer or operator with a wide range of information on the profitability of a system that cannot be obtained exclusively by traditional methods. So in work [25] a model of a building based on exergy is presented. The authors assess the potential of exergy use in increasing the efficiency of the construction sector. In work [26] it is indicated that the exergy model of the building allows to reduce the energy consumption of the building by 36 %. And in the work [27] examples of the implementation of technology for the construction of buildings with low energy consumption (LowEx) or, in other words, low-energy building systems are presented.

In work [28] the minimization of the total costs for the building and its operation: financial, energy and exergy is carried out, dependences of exergy on the thickness of the walls are obtained.

A thermoeconomic analysis of the energy modernization of buildings using VIP – vacuum insulation panels was performed in the work [29].

In the study [30], an exergoeconomic and ecological-economic analysis of the building heating system was carried out using the SPECO and Lowex methods. The heating system of a building is examined from the heat source (generating component) to the building envelope. This study uses the Lowex approach based on static calculation methods, which may not be very accurate compared to dynamic calculation methods.

There is a large number of works in which exergy, exergoeconomic, thermoeconomic analysis of various equipment and engineering systems is carried out, for example [31–37]. The articles [38, 39] consider the issues of energy saving in central air conditioning systems by optimizing the parameters of their functioning based on the method of thermoeconomics.

The “Average Cost Theory” approach to the analysis of an energy conversion system with gas recovery and intercooling is described in [40].

From the analysis of the above literature, it follows that exergy analysis was practically not used in order to jointly optimize the enclosing structures (heat-shielding shell) of the building and engineering equipment. It should be noted that buildings with a low level of exergy provide significant prospects for the design of buildings with high performance characteristics. Therefore, this article describes a new approach to optimizing the thermal insulation of buildings based on the method of thermal economics, which improves the energy efficiency of buildings.

The purpose of the research in this article is to develop a thermoeconomic model of the thermal protective shell of buildings together with a heating system, taking into account the composition of the enclosing structures and the peculiarities of the course of thermodynamic processes in the enclosing structures and engineering equipment. To achieve this goal, the article solves a number of particular tasks: determining the main factors affecting the energy efficiency of buildings, formalizing energy consumption processes, analyzing the analytical relationships and results obtained.

2. Methods

When optimizing the thermal insulation of buildings together with the heating system, it is necessary to provide the required exergy of internal air in the premises of the building. The thermoeconomic analysis considers and takes into account the exergy losses that occur during the transmission and transformation of energy in the heat-protective envelope of the building and individual elements of the heating system, as well as the economic costs associated with the creation and operation of the building envelope and individual elements of the heating system.

At the substantive level, the optimization problem solved in this article is formulated as follows: *find the minimum of the reduced costs for the creation and operation of the building envelope together with the heating system while maintaining the required microclimate in the building.*

The object of research is a reconstructed building of a computing center with a total area of 1764 sq. M. and a height of 12 m, the existing enclosing structures – slag concrete panels without thermal insulation. During the research, options for reconstruction using several types of thermal insulation were considered. At the same time, for each type of thermal insulation and heating system equipment, individual service lives declared by manufacturers were considered. Heating system – two-pipe water with artificial circulation of the coolant. The requirements for heat energy for heating needs were taken into account. Modeling was carried out using climate data for the city of Moscow. In the course of modeling, the estimated price of consumed heat energy is 2000 rubles/Gcal, the price of consumed electrical energy is 4 rubles kW*hour.

The schematic diagram of the object under study, for which the thermoeconomic model is being created, is shown in Fig. 1. Fig. 1 indicates the following: zone I is the individual heating point (IHP); zone II is the heating devices in serviced premises; zone III is the building envelope; 11 is the heat exchanger; 12 is the circulation pump IHP; 21 are the heating devices; 31 is the thermal insulation of the building envelope (walls); 32 is the coating insulation; 33 are the windows; T1, T2 are the supply and return pipelines of the coolant.

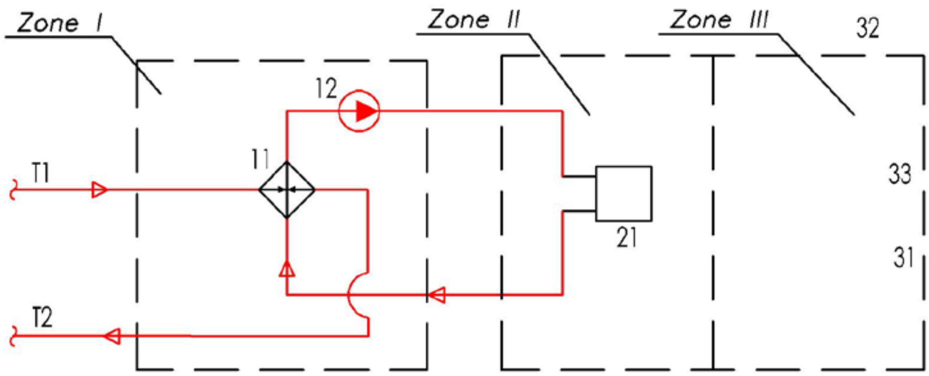

Figure 1.Schematic diagram of the object under consideration.

In the method of thermoeconomics, the main indicator of efficiency that ultimately determines "to be or not to be" of a technical system is the reduced costs Z, referred to a certain period of time [23, 41]:

$$Z = E_{hi} \cdot K_i + \Omega_i, \tag{1}$$

where Z is the annual reduced costs, rubles; E_{hi} is the discount coefficient (coefficient of efficiency of investments in the i^{th} element of the heating system, thermal insulation of enclosing structures, etc.); K_i is the investment in the i^{th} element of the heating system, thermal insulation of enclosing structures, etc., rub.; Ω_i is the operating costs for the i^{th} heating system, thermal insulation of enclosing structures, etc., rub.

The discount factor is calculated depending on the refinancing rate and the time during which it is expected to make a profit:

$$E_{hi} = \frac{1}{(1-r)^{n_i}}, \tag{2}$$

where r is the discount rate (refinancing rate, inflation, expected profitability, etc.); n_i is the estimated period of profit (project implementation period, service life of the i^{th} element, etc.), year.

Operating costs for the i^{th} element are determined by the formula:

$$\Omega_i = b_i K_i + \sum_{i=1}^{m} S_i^{en} + S_{0i}, \tag{3}$$

where b_i is the coefficient of deductions for depreciation and repair of the i^{th} element; $\sum_{i=1}^{m} S_i^{en}$ is the total annual energy costs for each i^{th} resource, rubles; S_{0i} is the costs of maintenance and current repair of i^{th} element, salary to personnel, etc., rub.

The decisive advantage of this indicator (reduced costs) is the ability to assess how effective the investment will be in various elements of the heating system and thermal insulation of the building envelope, as well as to assess the amount of subsequent operating costs while maintaining the required microclimate in the building.

In all processes subjected to thermoeconomic analysis, it is advisable to separate energy and non-energy costs, since the former are directly related to the thermodynamic characteristics of both the system as a whole and its zones and sections. Non-energy costs are also associated with thermodynamic parameters, but the nature of these relationships is much more complex; corresponding dependences in analytical or any other form can be obtained for each type of system.

According to [23], the annual reduced costs are determined by summing the product of the annual consumption of each type of resource by the cost of its unit of measurement (energy costs) and the amount of costs attributable to each unit of equipment in operation (its cost, upkeep, maintenance, staff salaries, regulatory deductions and etc.). Is the non-energy costs:

$$Z = \sum_{i=1}^{m} S_i^{en} + \sum_{i=1}^{n} S_i^{noten}, \tag{4}$$

where $\sum_{i=1}^{m} S_i^{en}$ is the total annual energy costs for each i^{th} consumed resource, rubles; $\sum_{i=1}^{n} S_i^{noten}$ is the total annual non-energy costs for each i^{th} element (equipment) of the optimized system; m is the number of types of resources (energy) used during the operation of the engineering equipment of the building in question; n is the number of units of elements (equipment) of the system under consideration.

The division of costs into energy and non-energy costs is possible by combining equations (1) and (3). Then the total energy costs directly related to the thermodynamic characteristics of the system, including the cost of all energy flows entering the system, will be

$$\sum_{i=1}^{m} S_i^{en} = \sum_{i=1}^{m} e_i \cdot c_i \cdot t_{hp}, \tag{5}$$

where e_i is the applied exergy of the i^{th} type, J/s; c_i is the price of exergy of the i^{th} type, rubles/J; t_{hp} is the estimated operating time of the heating system per year (for the heating period), s.

The total non-energy costs take into account capital investments in the creation (modernization) of heating system elements and thermal insulation of enclosing structures, as well as labor costs for operating the system (costs for maintenance, maintenance, disposal, salary for personnel, etc.):

$$\sum_{i=1}^{n} S_i^{noten} = \sum_{i=1}^{n} \left(\left(E_{hi} + b_i \right) \cdot K_i + S_{0i} \right), \tag{6}$$

Expression (6) allows one to obtain particular mathematical models of the formation of non-energy costs for the i^{th} element during the heating period:

$$z_i = \frac{S_i^{noten}}{t_{hp}} = \frac{\left(E_{hi} + b_i\right) \cdot K_i + S_{0i}}{t_{hp}}. \tag{7}$$

To solve the optimization problem solved in the article, a thermoeconomic model of the heat-protective shell of a building is developed, which is presented in the form of several separate zones connected in series. Each zone includes either the thermal insulation of the enclosing structures, or a group of heating system elements that have relative independence within the system. Such a linearized representation of the object of research greatly simplifies further calculations by excluding from consideration individual technological connections that do not affect the energy consumption of the object. When constructing a thermoeconomic model of the heat-protective shell of a building envelope, a number of restrictions and assumptions are used. For example, the effect of heat engineering non-uniform sections of enclosing structures (heat-conducting inclusions) on heat losses through the shell of buildings is not taken into account. In the calculations, it is assumed that the enclosing structures are thermally homogeneous. Reducing heat loss by taking into account inhomogeneous sections of enclosing structures is discussed in detail in [42]. The assumption is also used that the thermophysical properties of materials and the thermotechnical characteristics of the enclosing structures remain unchanged over time.

Fig. 2 shows a thermoeconomic model of the research object, which includes a heating system and thermal insulation of enclosing structures. Such a model is applicable for buildings in which there is no central ventilation and air conditioning systems.

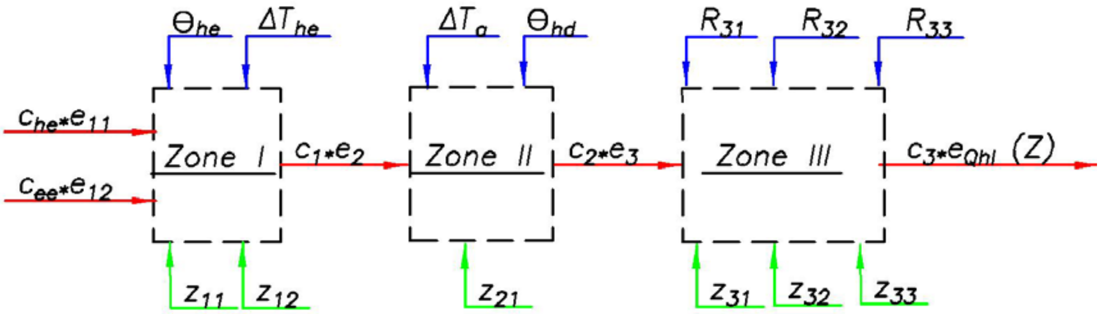

Figure 2. Thermoeconomic model of the heating system and thermal insulation of enclosing structures, presented in the form of the series of connected zones.

Through the control surface of the model from an external source to the first zone, the exergy e_{11} is supplied – the exergy of the coolant coming from the boiler room and e_{12} is the exergy to the drive of the electric motor of the circulation pump. The price of exergy supplied from an external source is known and is equal to: c_{he} is the price of consumed heat energy, c_{ee} is the price of consumed electrical energy. Also, through the control surface of the model, non-energy costs for each i^{th} element (equipment) of the optimized system are brought to different zones: z_{11} is the specific fixed costs for IHP equipment; z_{12} is the unit fixed costs for pumping equipment; z_{21} is the specific fixed costs for heating devices; z_{31} is the specific fixed costs for wall insulation; z_{32} is the specific fixed costs for thermal insulation of the coating; z_{33} is the specific fixed costs for windows. In each zone of the thermoeconomic model, energy dissipation and an increase in equipment costs occur, which leads to an increase in the specific cost of exergy: c_1, c_2, c_3 are the specific cost of exergy after the I, II, and III zones, respectively.

During the operation of the research object, thermal processes are the most important, therefore, variables are used as the optimized variables that allow the development of a thermoeconomic model and it is relatively easy to determine the temperature conditions of the processes in the research object. These variables are as follows: Θ_{he} is the temperature difference in the ITP heat exchanger; ΔT_{he} is the change in the temperature of the circulating heat carrier in the heat exchanger; Θ_{hd} is the temperature head in the heating device; ΔT_a is the change in the temperature of the air heated in the heater; R_{31} is the reduced total thermal resistance of enclosing structures (walls); R_{32} is the reduced total thermal resistance of the coating; R_{33} is the reduced total thermal resistance of the windows.

Taking into account the accepted designations, equation (1) can be represented as:

$$Z = \left(e_{11} \cdot c_{he} + e_{12} \cdot c_{ee} + z_{11} + z_{12} + z_{21} + z_{31} + z_{32} + z_{33}\right) \cdot t_{hp}. \tag{8}$$

Moreover, $Z \to \min$.

The presentation of the thermoeconomic model of the research object in the form of a series of sequentially connected zones allows expressing the exergy and non-energy costs supplied to each of the zones in the form of functional dependences on the exergy flow leaving the considered zone and the optimized variables affecting this zone.

Then the amount of exergy supplied to various elements of the heating system from an external source e_i (Fig. 2), and non-energy costs for elements of the heating system and thermal insulation of the enclosing structures z_j are generally described as follows:

$$\left.\begin{array}{l} e_{11} = E_{11}\left(e_2, \Delta T_{he}, \Theta_{he}\right) \\ z_{11} = Z_{11}\left(e_2, \Delta T_{he}, \Theta_{he}\right) \\ e_{12} = E_{12}\left(e_2, \Delta T_{he}, \Theta_{he}\right) \\ z_{12} = Z_{12}\left(e_2, \Delta T_{he}, \Theta_{he}\right) \\ z_{21} = Z_{21}\left(e_3, \Delta T_a, \Theta_{hd}\right) \\ z_{31} = Z_{31}\left(e_{Qhl}, R_{31}, R_{32}, R_{33}\right) \\ z_{32} = Z_{32}\left(e_{Qhl}, R_{31}, R_{32}, R_{33}\right) \\ z_{33} = Z_{33}\left(e_{Qhl}, R_{31}, R_{32}, R_{33}\right) \end{array}\right\}, \quad (9)$$

where e_i is the amount of exergy, E_i is a function that describes the change in exergy, z_j is the amount of non-energy costs, Z_j is a function that describes the change in non-energy costs.

Separate zones of the thermoeconomic model are interconnected. This connection can be represented in the form of a functional dependence on the exergy flow leaving the zone and the optimized variables affecting the zone under consideration:

$$e_2 = E_2\left(e_3, \Delta T_a, \Theta_{hd}\right); \quad e_3 = E_3\left(e_{Qhl}, R_{31}, R_{32}, R_{33}\right). \quad (10)$$

There are connections between the variables being optimized, which requires considering the problem of minimizing the value of reduced costs as a problem of optimizing a function of several variables in the presence of constraints such as equalities (communication equations), i.e. as the problem of finding a conditional extremum. Such problems are successfully solved by one of the methods of conditional optimization, for example, the method of undefined Lagrange multipliers [41].

The minimum of the reduced costs Z of the object under study is determined by the thermodynamic perfection of the processes of heat transfer and energy consumption, which depend on the temperature head Θ and changes in the coolant temperatures ΔT in heat exchangers, thermal resistances of the enclosing structures R, which, in their turn affect the cost of equipment and thermal insulation of enclosing structures. And, the more thermodynamically perfect the system, the higher its cost (Fig. 3).

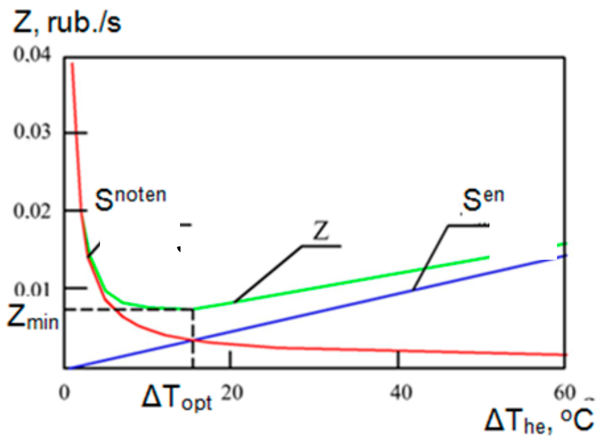

Figure 3. Dependence of reduced costs Z from the change in the temperature of the coolant in the heat exchanger ΔT_{he}.

The selected optimized variables affect the investment in the heating system equipment and the thermal insulation of the enclosing structures, and during subsequent operation, these variables determine the operating modes of the research object, which affect the operating costs. Therefore, in order to find the optimal value of the reduced costs Z, it is necessary to obtain analytical dependences of the cost indicators on the data of the optimized variables. The range of variation of the optimized variables is due to the physics of thermal processes in the corresponding structures and equipment.

The resulting dependences of investments in equipment and materials are presented below.

Investment in heat exchange equipment of the ITP will be:

$$K_{11i}\left(Q_{hl},\Theta_{he},k_i^{he}\right)=\frac{N_{11i}+M_{11i}\cdot Q_{hl}}{k_i^{he}\cdot\Theta_{he}}, \quad (11)$$

where K_{11i} is the investment in the i-type heat exchanger, rubles; Q_{hl} is the heat loss of the building through the enclosing structures (heating system performance), J/s; k_i^{he} is the heat transfer coefficient of the i-type heat exchanger, W/m^2*K; N_{11i}, M_{11i} is the numerical coefficients determined for heat exchangers of the i^{th} type.

The investment in the circulation pump will be:

$$K_{12i}\left(\Delta T_{he},Q_{hl}\right)=\frac{N_{12i}+M_{12i}\cdot Q_{hl}}{c_{hc}\cdot\rho_{hc}\cdot\Delta T_{he}}, \quad (12)$$

where K_{12i} is the investment in the circulation pump of the i^{th} type, rubles; ρ_T is the density of the heat carrier kg/m^3; c_{hc} is the heat capacity of the coolant, Jm^3*K; N_{12i}, M_{12i} is the numerical coefficients determined for circulation pumps of the i^{th} type.

The investment in heating devices will be:

$$K_{21i}\left(Q_r,\Theta_{hd},k_i^{hd}\right)=\frac{N_{21i}+M_{21i}\cdot Q_{hl}}{k_i^{hd}\cdot\Theta_{hd}}, \quad (13)$$

where K_{21i} is the investment in heating devices of the i^{th} type, rubles; k_i^{hd} is the heat transfer coefficient of the i^{th} type heater, W/m^2*K; N_{21i}, M_{21i} is the numerical coefficients determined for type i heaters.

The investment in wall insulation will be:

$$K_{31i}\left(R_{31i}\right)=F_w\cdot\left(N_{31i}+M_{31i}\cdot R_{31i}\right), \quad (14)$$

where K_{31i} is the investment in wall insulation with type i thermal insulation, rubles; R_{31i} is the heat transmission resistance of thermal insulation of the i^{th} type, m^2*K/W; F_w is the the area of the enclosing structures (walls) of the building, m^2; N_{31i}, M_{31i} is the numerical coefficients determined for type i thermal insulation.

Investment in coatings insulation will be:

$$K_{32i}\left(R_{32i}\right)=F_{\text{cov}}\cdot\left(N_{32i}+M_{32i}\cdot R_{32i}\right), \quad (15)$$

where K_{32i} is the investment in the insulation of coatings with thermal insulation of the i^{th} type, rubles; R_{32i} is the heat transmission resistance of thermal insulation of the i^{th} type, m^2*K/W; F_{cov} is the area of coverage of the building, m^2; N_{32i}, M_{32i} is the numerical coefficients determined for thermal insulation of the i^{th} type.

Investment in insulation (replacement) of windows will be:

$$K_{33i}\left(R_{33i}\right)=F_{ws}\cdot\left(N_{33i}+M_{33i}\cdot R_{33i}\right), \quad (16)$$

where K_{33i} is the investment in insulation (replacement) of windows of the i^{th} type, rubles; R_{33i} is the reduced total thermal resistance of windows of the i^{th} type, m²*K/W, F_{ws} is the area of the building windows, m²; N_{33i}, M_{33i} is the numerical coefficients determined for windows of the i^{th} type.

3. Results and Discussion

The solution of the problem of minimizing the value of the reduced costs, taking into account the obtained dependences of capital investments, as well as analytical expressions describing the processes occurring in individual elements of the heating system, makes it possible to determine the preferred option d_{po} of the enclosing structures (heat-shielding shell) of the building and engineering equipment in order to increase the energy efficiency of buildings under construction and renovation.

In the course of the research, it was revealed that the optimized variables to varying degrees affect the value of the reduced costs (Table 1). The reduced total thermal resistance of enclosing structures (walls, coatings, windows) have the greatest influence on the value of the reduced costs. A change in the temperature of the air heated in heating devices ΔT_a has practically no effect on the value of the reduced costs.

Table 1. Ranking Optimized Variables

Variable	Parameter weight
R_{31}	0.312
R_{32}	0.262
R_{33}	0.206
Θ_{he}	0.102
Θ_{hd}	0.089
ΔT_{he}	0.023
ΔT_a	0.006

Examples of the dependence of the function of reduced costs on R_{32} and Θ_{he} are shown in Fig. 4. Fig. 4 shows that the reduced costs have clearly expressed minima for the corresponding values of the optimized variables. These minima, through the reduced resistances to heat transfer of the enclosing structures, determine the optimal thickness of the additional layer of thermal insulation used in the reconstruction of the building under study, and also determine the optimal temperature head or temperature changes of the coolant during the operation of the heating system.

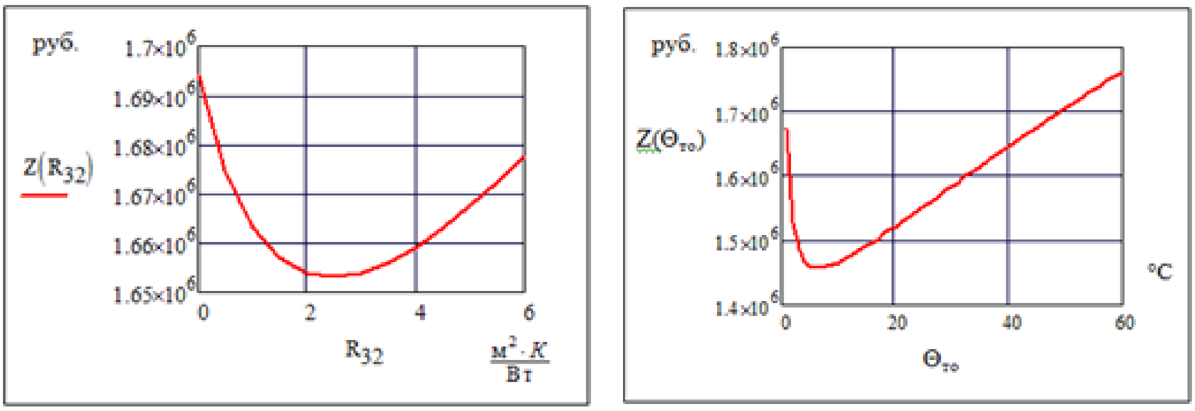

Figure 4. Dependences of the reduced cost function on R_{32} and Θ_{he}.

In the course of the research, possible options for insulating enclosing structures (heat-shielding shell) of the building d_i and the selected engineering equipment for the investigated building were also formed. Each option is a set of measures for the insulation of enclosing structures and the modernization of heating equipment in various combinations (Table 2).

Table 2. Developed options for insulation of enclosing structures and modernization of heating equipment

No	List of options d_i	Option implementation cost, C_i, million rubles	Reduced costs, Z_i, million rubles	Change in reduced costs, ΔZ_i, million rubles	$\Delta Z_i / C_i$
1	Project option	–	2.019	–	
2	Replacement of the pump and heat exchanger IHP	0.283	1.653	0.365	1.292
3	Insulation of the coating	0.365	1.616	0.402	1.102
4	Replacement of windows	0.604	1.605	0.414	0.685
5	Replacement of the pump and heat exchanger IHP + insulation of the coating	0.643	1.677	0.342	0.532
6	Replacement of the pump and heat exchanger IHP + replacement of windows	0.879	1.665	0.354	0.402
7	Insulation of the coating + replacement of windows	0.97	1.596	0.423	0.436
8	Replacement of the pump and heat exchanger IHP + insulation of the coating + replacement of windows	1.239	1.656	0.363	0.189
9	Wall insulation	1.345	1.292	0.727	0.54
10	Replacement of the pump and heat exchanger IHP + wall insulation	1.569	1.345	0.670	0.427
11	Insulation of the coating + wall insulation	1.716	1.277	0.742	0.434
12	Replacement of the pump and heat exchanger IHP + wall insulation + coating insulation	1.93	1.339	0.680	0.352
13	Wall insulation + replacement of windows	1.949	1.255	0.764	0.392
14	Replacement of heating devices	2.047	1.371	0.648	0.316
15	Replacement of the pump and heat exchanger IHP + wall insulation + replacement of windows	2.165	1.327	0.692	0.319
16	Wall insulation + insulation of the coating + + window replacement	2.314	1.227	0.792	0.342
17	Replacement of the pump and heat exchanger IHP + replacement of heating devices	2.33	1.432	0.587	0.252
18	Insulation of the coating + replacement of heating devices	2.365	1.365	0.654	0.277
19	Replacement of the pump and heat exchanger IHP + wall insulation + insulation of the coating + + replacement of windows	2.525	1.171	0.848	0.336
20	Replacement of windows + replacement of heating devices	2.565	1.356	0.663	0.259
21	Wall insulation + replacement of heating devices	2.805	1.073	0.946	0.337
22	Insulation of the coating + replacement of windows + replacement of heating devices	2.882	1.349	0.669	0.232
23	Insulation of the coating + wall insulation + + replacement of heating devices	3.123	1.067	0.952	0.305
24	Thermal insulation of walls + replacement of windows + replacement of heating devices	3.323	1.058	0.961	0.289
25	Wall insulation + insulation of the coating + replacement of windows + replacement of heating devices	3.64	1.052	0.967	0.266
26	Replacement of the pump and heat exchanger IHP + wall insulation + insulation of the coating + + replacement of windows + replacement of heating devices	3.851	1.026	0.992	0.258

Each reconstruction option involves investment in its implementation, which in turn determines the reduced costs corresponding to this option. Options in which the cost of implementation increases, but the reduced costs do not decrease, are excluded from further consideration. The remaining options allow you to build a graph of reducing the reduced costs during the operation of the computing center building, depending on the increase in the cost of implementing a particular reconstruction option C_{di}. From the graph, you can determine the most rational reconstruction option, depending on the amount of funds available (Fig. 5).

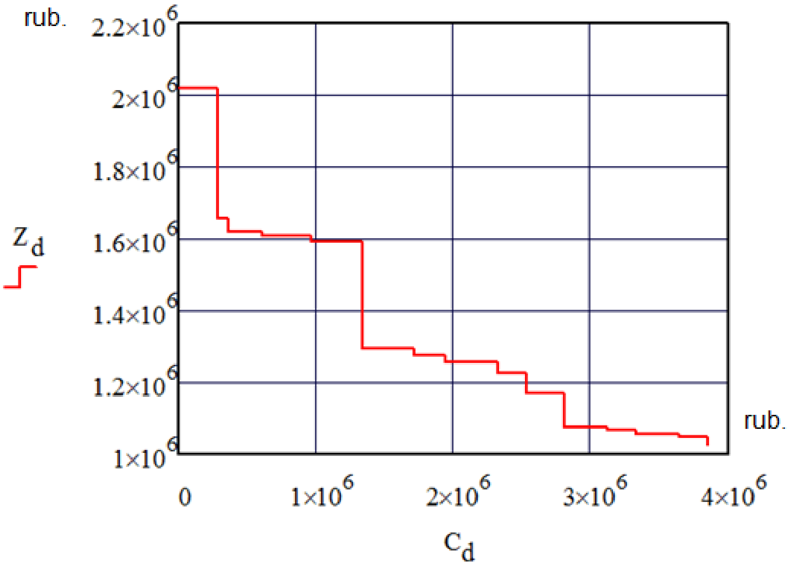

Figure 5. Dependence of the reduced cost function on the cost of the option of insulating enclosing structures (heat-shielding shell) of the building and the selected engineering equipment.

The approach proposed in the article to the thermoeconomic analysis and optimization of the enclosing structures (heat-shielding shell) of a building and engineering equipment (heating system) makes it possible to reduce the reduced costs of their creation and operation by an average of 20–25 % in comparison with traditional approaches, and reduce the energy consumption by 30–34 % (Fig. 6). Fig. 6 shows the dependence of the energy consumption of a building at different ambient temperatures. It can also be seen that the percentage reduction in energy consumption of a building is obviously greater than the possible error arising from the introduction of restrictions and assumptions in the development of a thermoeconomic model.

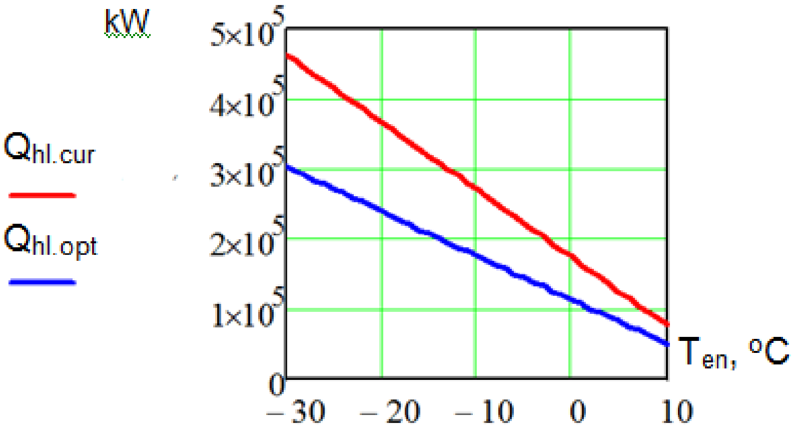

Figure 6.Reducing building energy consumption at different ambient temperatures.

Analysis of the results obtained shows their convergence with the results of similar studies, for example [28], but the results obtained take into account not only the complex composition of the enclosing structures, their cost, but also the peculiarities of the course of thermodynamic processes in the enclosing structures and engineering equipment. Analysis of the results obtained shows their convergence with the results of similar studies, but the results obtained take into account not only the complex composition of the enclosing structures, their cost, but also the peculiarities of the course of thermodynamic processes in the enclosing structures and engineering equipment. For example, in [28], graphs of financial costs for the creation and power supply of a brick building are given, which are similar in terms of the dependences of the reduced cost function in Fig. 4. At the same time, the decrease in financial costs for the creation and power supply of the building with the optimal thickness of thermal protection amounted to an average of 25–28 %, and the reduction in energy consumption for the creation and energy supply of the building was 30–40 %, which is comparable to the results obtained in this article. The new results obtained show the possibility of their application in practice in order to increase the energy efficiency of buildings under construction and reconstructed ones.

Thus, a thermoeconomic model of the heat-protective envelope of the building has been obtained together with the heating system, which allows optimizing the heat-protective envelope of the building in order to increase the energy efficiency of buildings under construction or reconstruction. The resulting model is quite simple and suitable for use not only in engineering practice, but also in the educational process.

4. Conclusions

1. The article reviews the literature on energy conservation, energy efficiency improvement of buildings under construction or reconstruction.

2. Applied exergy analysis to the heat-protective envelope of the building and engineering equipment, considered as a single energy system.

3. A thermoeconomic model of the thermal protective shell of buildings together with a heating system has been developed, taking into account the composition of the enclosing structures and the peculiarities of the course of thermodynamic processes in the enclosing structures and engineering equipment.

4. Expressions are given in general form that allow solving the problem of minimizing the reduced costs for the creation and operation of the enclosing structures (heat-shielding shell) of a building and engineering equipment.

5. Analytical dependences of investments in heating system equipment and thermal insulation of enclosing structures on the optimized variables have been obtained.

6. It was revealed that the reduced total thermal resistance of enclosing structures (walls, coatings, windows) has the greatest influence on the value of the reduced costs.

7. The graphs of the function of reduced costs from the optimized variables R_{32} and Θ_{he} and to are built. It is shown that when using the developed thermoeconomic model, the costs are reduced on average by 20–25 % compared to traditional approaches, and the energy consumption of the building is reduced by 30–34 %.

8. The analysis of the obtained analytical dependencies and results is carried out, their convergence with the results of similar studies is shown.

9. The results of the study can be used by investors, design and operating organizations to assess the energy efficiency of buildings under construction or reconstruction and to select the optimal option for the building envelope (heat shield) and engineering equipment.

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