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BRIDGES AND TUNNELS: THEORY, RESEARCH, PRACTICE

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MODERN ORGANIZATIONAL AND TECHNOLOGICAL MODELS OF ENERGY EFFICIENCY IN CONSTRUCTION

Purpose. The research is devoted to solving an important scientific and practical problem, which consists in the creation and implementation of integrated organizational and technological models of construction (IOTMC). Such models are intended to ensure a high level of energy efficiency of construction objects at all stages of their life cycle. The main purpose is the development of methodological foundations of comprehensive management of construction processes, which makes it possible to use material, labor, and energy resources efficiently, to reduce operational costs, and to increase the technological productivity of construction works. **Methodology.** The methodology is based on the integration of organizational and technological solutions aimed at a comprehensive reduction of energy consumption. Such solutions include the optimization of the sequence of construction operations, the application of technologically efficient methods of installation and finishing, the management of material flows with minimization of resource losses, as well as the control of the level of energy consumption at every stage of construction. The integrated implementation of these organizational and technological measures ensures an increase in the energy efficiency of buildings, a reduction of operational costs, and the rational use of resources both during the construction process and throughout the subsequent operation of the facilities. **Findings**. The analysis of modern approaches to the organization of construction processes demonstrates the necessity of introducing integrated management methods that combine organizational and technological solutions while taking into account the energy efficiency of construction projects. Traditional models are primarily focused on timelines and financial indicators, whereas the management of energy consumption and resources remains insufficiently developed. The optimization of construction processes requires the coordination of works and technological schemes aimed at minimizing energy expenditures during the preparatory, installation, finishing, and operational stages. **Originality**. A concept of integrated energy resource management in construction production has been developed, which is focused on ensuring energy efficiency. This concept combines planning, coordination, and control of technological processes with the aim of achieving an optimal balance between the quality of work execution, construction timelines, and the rational use of energy, material, and labor resources. **Practical value.** A mathematical and simulation-based toolkit for the optimization of integrated organizational and technological processes of energy-efficient construction has been introduced into practice. It has been developed on the basis of systems analysis methods, mathematical programming, and graph theory, and it makes it possible to determine rational sequences of work execution, minimize energy consumption, and increase the productivity of construction production.

Keywords: organizational and technological models; energy efficiency of construction; mathematical and simulation-based toolkit; optimization of construction processes; integrated models

Introduction

Energy efficiency in construction today is one of the key priority tasks of modern civilization, driven both by global environmental challenges and the economic feasibility of reducing energy consumption. The construction sector remains one of the most energy-intensive industries, and its impact on the ecological situation is significant, as approximately 40 % of the world's energy consumption is associated with the construction and operation of buildings (Moonen, Nunlay, & Clark, 2019). In this context, the implementation of modern organizational and technological models of energy efficiency becomes essential for ensuring sustainable development and optimizing resource expenditures in construction (ДСТУ, 2014; Фаренюк, Філоненко, & Тимофєєв, 2017).

Despite significant progress in the field of energy-efficient construction, the practical implementation of modern organizational and technological models faces a number of challenges. One of the main issues is the lack of a systematic approach to integrating technological, design, and organizational solutions. Often, individual energy-saving measures are implemented fragmentarily, which prevents achieving the maximum possible effect.

Another problem is the insufficient use of high-tech materials and innovative structural solutions in the construction process. Many enterprises rely on traditional materials, which reduce the potential for energy savings and increases operational costs. In addition, the absence of standardized methods for evaluating the effectiveness of energy-saving technologies complicates the comparison of different solutions and the making of well-founded managerial decisions (Арутюнян, Жамілов, & Веремій, 2023). Thus, the issue boils down to the need for a comprehensive approach that combines technological, organizational, and managerial solutions integrated into modern models of energy-efficient construction (Zaborona, 2022).

Contemporary approaches to energy efficiency involve the comprehensive integration of technological, organizational, and managerial solutions, which allows not only the reduction of energy consumption but also the improvement of the quality and durability of buildings. An important component is the use of innovative materials with enhanced thermal insulation properties, energy-saving technologies for heating, ventilation, and lighting, as well as digital systems for managing construction processes, which provide real-time monitoring of energy consumption.

The increasing requirements of international and national standards for building energy efficiency necessitate the implementation of organizational and technological models that allow for the systematic evaluation and management of energy resources. In particular, within the framework of European "green building" initiatives, there is an emphasis on the need to certify buildings according to criteria of energy efficiency and the minimization of greenhouse gas emissions (CREA, 2022).

In light of the current challenges, the Ukrainian construction sector faces the task of not only restoring the destroyed infrastructure, but also creating more sustainable and energy-efficient buildings (Підсумки, 2019; Розпорядження, 2021). This will require the active participation of government, business and the public, as well as the involvement of international support and investment.

External walls, as one of the important components of the enclosing structure, remain the primary source of heat loss throughout the whole period of building's operation. Despite significant progress in the development of innovative construction materials, many manufacturers still use outdated technologies, leading to high energy costs and significant financial losses.

To solve this problem, it is necessary to introduce the latest materials and technologies that provide better thermal insulation. These include insulation based on aerogels, nanomaterials and vacuum insulated panels, which have significantly higher thermal insulation properties compared to traditional materials. It is also important to use energy-efficient windows and doors that reduce heat loss through external enclosing structures.

Additionally, to reduce heat loss, it is advisable to use systems of ventilated facades, which not only improve the thermal insulation properties of buildings, but also ensure effective moisture removal, preserving the operational characteristics of insulation. The use of reflective and heat-accumulating coatings on the walls allows to reduce heat loss in winter and overheating in summer. Implementation of such innovative solutions in construction will increase the energy efficiency of buildings, reduce heating and cooling costs, and improve living comfort. It is also important to actively promote governmental programs and incentives to support the implementation of energy-efficient technologies, which will ensure the sustainable development of the construction sector and reduce the negative impact on the environment.

Purpose

Therefore, the aim of this study is the systematic investigation and development of modern organizational and technological models of energy efficiency in construction, capable of providing comprehensive optimization of construction processes while taking into account economic, environmental, and technical aspects. Direction is to focus on the development of theoretical and practical recommendations for the optimization of technological processes related to enclosing structures in order to increase their energy efficiency.

Methodology

Wall materials, ceilings, doors, windows and ventilation systems have the main influence on energy consumption. Reducing energy consump-

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tion and using renewable energy sources in the construction sector is critical to reducing energy dependence and greenhouse gas emissions.

Analysis of the energy efficiency of the Ukrainian building stock, in accordance with the directives of the Council, the European Parliament and Ukrainian legislation (the Law of Ukraine "On the Energy Efficiency of Buildings") (Закон України, 2017), has showed that buildings in Ukraine have low energy efficiency, while energy consumption for their operation is relatively high.

The terms "energy conservation" and "energy efficiency" should not be confused, although they are closely related. Energy efficiency means the most efficient use of resources to meet needs through technological solutions. Energy conservation, on the other hand, aims to reduce the overall amount of energy consumed without significantly affecting the work performed or results achieved.

In other words, energy conservation focuses on reducing overall energy consumption, while energy efficiency aims to achieve optimal results or functions using the same or less energy. Both approaches are important for sustainable energy use and resource conservation.

Many modern new buildings have an unsatisfactory level of energy efficiency and energy conservation. Although Ukrainian building regulations require new buildings to be designed and built with appropriate energy characteristics and rational energy consumption, with detailed requirements outlined in the Technical Conditions Regulations to which buildings and their locations must comply, are often not met in practice. As a result, the energy quality of modern buildings is unsatisfactory.

Building enclosing structures, such as walls, roofs, floors and windows, play a crucial role in maintaining indoor heat and withstanding external environmental impacts. Effective enclosure systems can significantly reduce heat and energy losses, which contribute to more efficient use of heating and cooling. At the same time, low-quality or incorrectly installed enclosing elements can lead to significant heat loss and increased energy costs to maintain comfortable indoor conditions. For example, structures with high-quality thermal insulation can significantly reduce the need for heating in the winter and air conditioning in the summer, reducing utility costs for the population and improving the quality of life.

Many buildings, especially those designed according to modern standards, are highly energy efficient. However, a significant part of the population lives in buildings that were already energy inefficient at the design stage. Consequently, citizens actively take measures to improve living conditions by improving the characteristics of the building structures around them. For example, adding heat-insulating materials to the exterior layers of walls or roofs is an effective way to increase the building's insulating properties. This approach is particularly common in thermal modernization programs, implemented with investment and municipal funds, covering various types of buildings – from hospitals and kindergartens to schools and administrative buildings.

Findings

The most urgent problem right now is the destruction of the energy infrastructure as a result of air attacks by the aggressor country. Since October 10, 2022, Russia launched attacks on key energy infrastructure facilities in Ukraine, resulting in the blackouts, heating and hot water supply disruptions in all regions of the country. In just one day, 30% of Ukraine's energy system infrastructure was damaged. According to the official statement of the President of Ukraine dated November 19, 2022, about 50 % of the total infrastructure and generating capacities of the country's energy system was damaged. The aggressor country carries out active attacks on thermal power plants, boiler houses and substations, leading to a partial imbalance of the entire energy system of Ukraine. As of September 22, Russia's armed aggression has already damaged 349 critical infrastructure facilities in the field of heat supply, including 335 boiler houses (332 damaged, 13 destroyed), 11 thermal power plants (7 damaged, 4 destroyed) and 3 thermal power plants. The state plans to finance the reconstruction of the Okhtyrka and Chernihiv thermal power plants and centralized heat supply systems in Kremenchuk (Fig. 1).

This can lead to serious problems in the construction sector, since the main means of heating the residential buildings in Ukraine is a centralized system that provides approximately 60 % of all heating (Сердюк, В. Р., Сердюк, Т. В., & Франишина, 2019).

It is estimated that about 70 % of the total energy consumption in European buildings is used for heating and cooling the premises. Thus, measures

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aimed at reducing energy costs and increasing the efficiency of energy production have significant potential to improve the energy efficiency of buildings. Below is a diagram showing how heat losses are distributed through walls and ventilation systems in the energy balance of a building (Figure 2).

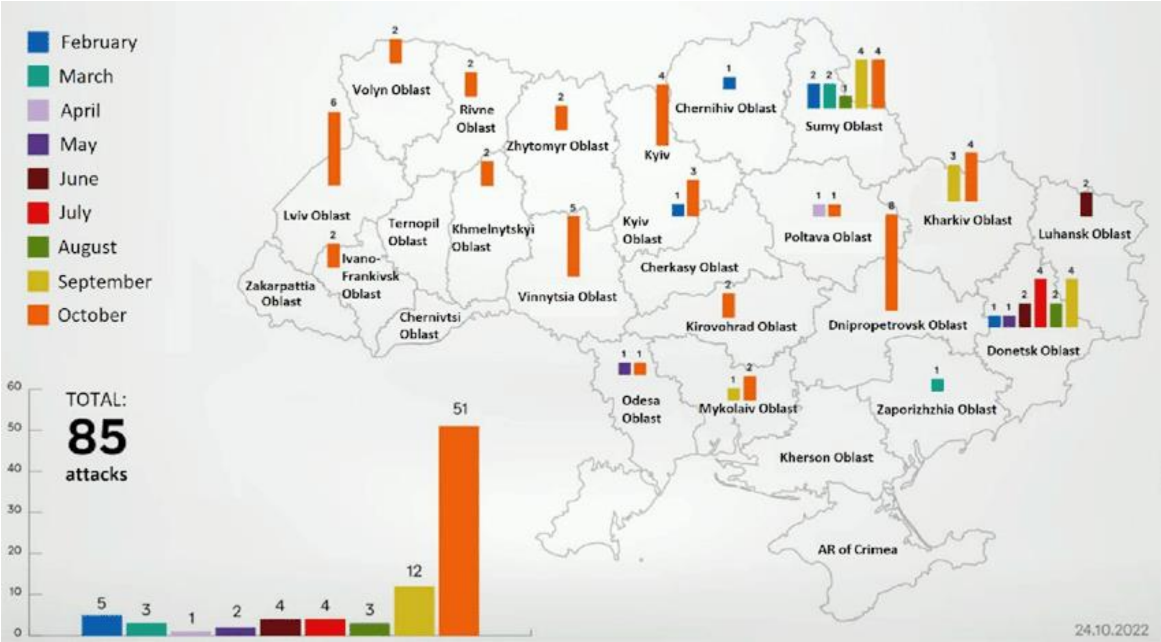

Fig. 1. Strikes of the Russian Federation Armed Forces
on electric power facilities at the time of October 24, 2022

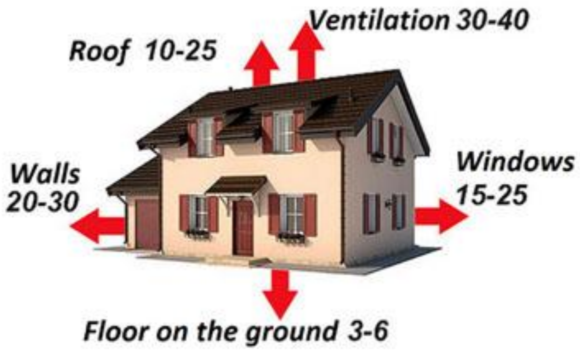

Fig. 2. Percentage ratio of heat losses
in a modern building

It is important to note that the main heat losses in the building are related to the enclosing structures, such as glazed windows, walls and roof, which account for about 60 … 70 % of the total energy balance. At the same time, ventilation systems are responsible for 30 … 40 % of losses. Therefore, it is extremely important to minimize these heat losses and efficiently use the obtained energy to ensure the energy efficiency of buildings.

The main structures for isolating the internal space of the building from the external environment are opaque (walls, doors) and transparent (windows, balconies, stained glass windows, lamps, etc.). They perform several important functions, such as protection from noise, moisture, wind and temperature fluctuations, and require special attention to ensure a comfortable microclimate for people.

An example of ineffective energy policy in construction is numerous "serial" buildings of the Soviet period. Nowadays, they rightfully have the status of morally and physically outdated housing. The ideology and economic conditions of that time required the designers to create universal structures that met the requirements of compactness, economy and speed of construction. However, in the 21st century, we observe only limited spaces and inconvenient planning. The main requirements for the enclosing structures were durability and strength, so the thermal efficiency indicators were not considered critical and were not evaluated in comparison with modern standards. Many of these buildings do not meet modern energy efficiency requirements and require additional insulation and soundproofing.

A separate problem is wooden windows in post-Soviet buildings, which accounted for up to 40 % of heat losses. Compared to the minimum standards of heat transfer resistance (0.75 … 0.6 m²·K/W), old windows have almost half the efficiency: 0.39 … 0.42 m²·K/W. Additionally, these designs suffered from excessive moisture and poor sealing compared to modern double-glazed windows (Fig. 3**).**

Fig. 3. Serial houses of the last century

The heat transfer coefficient of the structure is an important indicator of its thermal insulation. This coefficient is determined by the materials that make up the individual layers of the wall (structural layer, insulation, decoration) and their thickness. The general principle is that the lower the thermal conductivity coefficient of the material, the more effective its thermal insulation.

Thermal insulation is the main factor in determining the heat needs of the building and, accordingly, its operational costs. Well-insulated enclosure structures result in low values of the heat transfer coefficient (U) of these partitions, which helps to reduce energy losses and heating costs. Investments in high-quality thermal insulation and its proper installation allows to save during each heating period during the entire lifecycle of the building.

The lower the heat transfer coefficient, the better the thermal insulation of the partition. The value of the heat transfer coefficient is determined separately for: double-glazed windows, window and door frames, transoms, as well as linear heat transfer coefficients characterizing the thermal insulation of joints.

It is important to note that windows designed for energy-efficient buildings with high heat transfer coefficients are not intended for natural ventilation, which is typical of traditional construction. Such windows do not have an automatic ventilation mechanism, and their seals are carefully designed and made of high-quality materials. Therefore, when replacing windows in an energy-efficient building that uses natural ventilation, it is necessary to ensure that the new windows are equipped with special fans that will provide sufficient air flow into the room and allow the ventilation system to function properly.

Regarding the insulation of external walls, this is the most common and scientifically based solution in terms of building physics. However, in historical buildings, there may be situations when external facade insulation is not an acceptable option. In such cases it is possible to consider the option of internal wall insulation to improve thermal insulation.

The advantage of this approach is to preserve the original appearance of the facade, while simultaneously improving the energy efficiency of a separate room or specified room in the building, which is not subject to general thermal modernization.

It is important to consider that improperly performed internal insulation can lead to moisture in the walls and promote the mold growth. In addition, the external wall, which is traditionally in a heated zone, has the ability to accumulate heat and stabilize the temperature in the room. However, with internal insulation, this wall becomes vulnerable to the effects of frost, and is also subject to degradation due to precipitation and low temperatures.

When insulating from the inside, the main aspect is the diffusion resistance of the materials used for thermal insulation, which determines their ability to pass water vapor. There are two main methods of internal insulation:

Method with dense vapor barrier from the inside. A layer of thermal insulation (often using mineral wool or polyurethane foam) is applied to a wall with a wooden or metal base. Then a vapor barrier film is applied to form a dense layer that prevents moisture from entering the room into the insulating layer and avoiding condensation on the cold wall. The finishing layer is plaster or drywall, noting the necessity of effective ventilation, ensuring mechanical removal of water vapor to maintain the required level of humidity in the room.

Method using vapor-permeable materials. This approach uses materials that allow water vapor to freely penetrate, such as lime-silicate or aerated concrete panels. These materials have a porous structure, which allows them to absorb water vapor from the room and evenly distribute it across the entire surface. After that, the accumulated moisture is removed when the humidity in the room decreases.

These two approaches should be considered taking into account specific conditions and requirements for energy efficiency and ventilation of building structures.

In the first of the aforementioned insulation methods, a layer of insulation, typically mineral wool or polyurethane foam boards, is applied to a wall with a wooden or metal base. Then a vapor barrier film is applied to this layer to create a dense layer that prevents the penetration of moisture from the room into the insulation layer and avoids condensation on the cold wall. The next stage is the application of plaster or drywall, which serves as a finishing coating. It is important to ensure the effective operation of the ventilation system, providing for the removal of water vapor, especially in the case of mechanical ventilation, which ensures the maintenance of proper humidity level in the room.

The second method involves the use of materials that allow water vapor to freely penetrate, such as lime-silicate or aerated concrete panels. These materials have a porous structure that can absorb water vapor from the room and evenly distribute it over the entire surface. When the humidity in the room decreases, they release accumulated water vapor.

When using internal insulation, it is important to always analyze the humidity of the room and assess the possibility of condensation inside the wall, as well as the possibility of evaporation of accumulated moisture. This allows to make a correct choose of technology according to the needs of users and the operating conditions of the building.

Originality and practical value

A concept of integrated energy resource management in construction production has been developed, which is focused on ensuring energy efficiency. This concept combines planning, coordination, and control of technological processes with the aim of achieving an optimal balance between the quality of work execution, construction timelines, and the rational use of energy, material, and labor resources.

A mathematical and simulation-based toolkit for the optimization of integrated organizational and technological processes of energy-efficient construction has been introduced into practice. It has been developed on the basis of systems analysis methods, mathematical programming, and graph theory, and it makes it possible to determine rational sequences of work execution, minimize energy consumption, and increase the productivity of construction production.

Conclusions

Analyzing the theoretical and methodological aspects of using the external wall structures to increase the energy efficiency of construction complexes, we came to the conclusion that in modern conditions of constant risk of an energy crisis, including geopolitical factors, enclosing structures play a key role in building heat losses.

Having reviewed the implementation of technologies, we substantiated the effectiveness of energy-efficient measures in the construction sector of Ukraine and the EU. Demonstrating the feasibility of relevant projects, such as energy audits and the development of renewable sources, stimulates the further development of state energy efficiency policy in the long-term perspective.

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СУЧАСНІ ОРГАНІЗАЦІЙНІ ТА ТЕХНОЛОГІЧНІ МОДЕЛІ ЕНЕРГОЕФЕКТИВНОСТІ В БУДІВНИЦТВІ

Мета. Дослідження присвячене вирішенню важливої науково-практичної проблеми, яка полягає у створенні та впровадженні інтегрованих організаційно-технологічних моделей будівництва (ІОТМБ). Такі моделі призначені для забезпечення високого рівня енергоефективності будівельних об'єктів на всіх етапах їх життєвого циклу. Основною метою є розробка методологічних засад комплексного управління будівельними процесами, що дає змогу ефективно використовувати матеріальні, трудові та енергетичні ресурси, знижувати експлуатаційні витрати, підвищувати технологічну продуктивність будівельних робіт. **Методика.** В основі методики лежить інтеграція організаційних і технологічних рішень, спрямованих на комплексне зниження енергоспоживання. До таких рішень можна віднести оптимізацію послідовності будівельних операцій, застосування технологічно ефективних методів монтажу та фінішної обробки, управління матеріальними потоками з мінімізацією втрат ресурсів, а також контроль рівня енергоспоживання на кожному етапі будівництва. Комплексне впровадження цих організаційних і технологічних заходів забезпечує підвищення енергетичної ефективності будівель, зниження експлуатаційних витрат, раціональне використання ресурсів як в процесі будівництва, так і протягом всієї подальшої експлуатації об'єктів. **Результати**. Аналіз сучасних підходів до організації будівельних процесів свідчить про необхідність впровадження інтегрованих методів управління, які поєднують організаційні та технологічні рішення з урахуванням енергетичної ефективності будівельних проектів. Традиційні моделі в першу чергу орієнтовані на терміни і фінансові показники, в той час як управління споживанням енергії і ресурсами залишається недостатньо розвиненим. Оптимізація будівельних процесів вимагає узгодження робіт і технологічних схем, спрямованих на мінімізацію енерговитрат на підготовчому, монтажному, фінішному та експлуатаційному етапах. **Наукова новизна**. Розроблено концепцію інтегрованого управління енергетичними ресурсами в будівельному виробництві, яка орієнтована на забезпечення енергоефективності. Ця концепція поєднує планування, координацію та контроль технологічних процесів з метою досягнення оптимального балансу між якістю виконання робіт, термінами будівництва та раціональним використанням енергетичних, матеріальних і трудових ресурсів. **Практична значимість.** Впроваджено в практику математичний та імітаційний інструментарій оптимізації інтегрованих організаційних та технологічних процесів енергоефективного будівництва. Вона розроблена на основі методів системного аналізу, математичного програмування та теорії графів і дає змогу визначати раціональні послідовності виконання робіт, мінімізувати енерговитрати, підвищувати продуктивність будівельного виробництва.

Ключові слова: організаційно-технологічні моделі; енергетична ефективність будівництва; математичний та імітаційний інструментарій; оптимізація будівельних процесів; інтегровані моделі

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