BRIDGES AND TUNNELS: THEORY, RESEARCH, PRACTICE

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IMPROVEMENT OF ORGANIZATIONAL AND TECHNOLOGICAL SOLUTIONS IN THE CONSTRUCTION AND INSTALLATION OF ENERGY-EFFECTIVE CIVIL BUILDINGS BASED ON MATHEMATICAL MODELING

Purpose. The study is aimed at developing an integrated approach to improving organizational and technological solutions in the construction of energy-saving civil buildings by using mathematical modeling, which directly connects the technological construction schedule with the forecast of the energy efficiency of the facility. **Methodology**. A hybrid simulation model is proposed that combines discrete-event modeling (DES) of the construction process with a parametric assessment of the impact of installation deviations on heat loss. A typical nZEB building project was used for verification. The methodology integrates specialized approaches: optimization of visual surveillance placement based on 4D-BIM and construction schedule, which allows to identify "core" work zones in each period, and sensitivity analysis of energy performance to local deviations, adapted from the methodology for assessing airflows in data centers, which uses metrics of air distribution efficiency (e.g., RCI, SHI) – in our case, these metrics are converted into indicators of "technological integrity" of the enclosure. The modeling was implemented in the AnyLogic environment using simulation runs (n=100) and sensitivity analysis according to the Sobol method. **Findings**. The application of an optimized strategy (parallel installation of specialized systems + intermediate tightness control at points determined by 4D-BIM) allowed: to reduce the total construction duration from 218 to 196 days (-10 %), to reduce the average energy consumption from 24.3 to 16.1 kWh/m²/year (the deviation from the nZEB target value was reduced from +62 % to +7 %), and the number of critical installation errors by 5.3 times. Sensitivity analysis confirmed that the quality of vapor barrier installation and the time delay between insulation and sealing are the dominant factors (56 % of the total energy consumption variance). **Originality**. For the first time, a mathematical model was proposed that transforms organizational and technological planning into a tool for ensuring energy efficiency, and not only into managing deadlines and costs. Unlike existing BIM-to-energy approaches, the model takes into account dynamic construction conditions (crew changes, weather, logistics) as sources of risk of deviation from energy goals. Also, for the first time, metrics of air flow analysis from data centers were adapted to assess the quality of fence installation, which creates a new methodological bridge between industries. **Practical value**. The developed approach is technologically neutral, easily integrated into existing project management systems and allows contractors, energy auditors and state inspectors to make informed decisions that guarantee actual energy efficiency. This is especially relevant in the context of the implementation of nZEB requirements in the legislation of Ukraine.

Keywords: mathematical modeling of construction; energy-saving buildings; organizational and technological solutions; nZEB, 4D-BIM; simulation modeling; sensitivity analysis; energy efficiency at the construction stage

Introduction

The current stage of development of civil engineering is determined by a large-scale transition to the principles of sustainable development, which is reflected in the need to strengthen regulatory requirements for the energy efficiency of buildings.

However, the implementation of such high-precision projects in the conditions of modern construction production is accompanied by a number of organizational and technological challenges. First of all, the processes of construction of energy-saving buildings are characterized by increased complexity of coordination between specialized contracting organizations. Secondly, traditional planning methods, such as linear graphs or network models of the CPM/PERT type, do not take into account the dynamic relationships between technological operations, weather conditions, resource availability and requirements for the quality of installation of energy-efficient elements. Thirdly, the lack of integrated approaches to modeling the energy characteristics of structures and the logistics of the construction process simultaneously, which complicates the adoption of informed management decisions at the stage of work execution.

In this context, mathematical modeling acquires the status of a key scientific tool capable of providing a formalized description, analysis and optimization of complex building systems. Unlike empirical methods, mathematical models allow us to quantitatively assess the impact of various factors, such as the duration of individual operations, the thermal resistance of wall panels, etc., on the overall efficiency of the project. Modern approaches include the use of simulation modeling (discrete-event simulation, agent-based modeling) to predict resource loading, optimization algorithms (genetic, swarm, linear programming) to minimize time and costs under energy quality constraints, as well as machine learning methods to adaptively adjust plans based on data from the construction site. In addition, the integration of mathematical models with BIM environments allows us to create digital twins of construction processes, where each technological operation is associated with the corresponding energy parameters.

The relevance of this study lies in the fact that, despite significant achievements in the field of energy-efficient design, the issue of synchronization of organizational and technological solutions with energy saving requirements through mathematical modeling remains insufficiently studied, especially in markets with high fragmentation of the construction sector. Therefore, the purpose of this work is to develop scientifically sound approaches to improving organizational and technological solutions in the construction and installation of energy-saving civil buildings based on the integrated application of mathematical modeling methods aimed at ensuring compliance of actual energy efficiency indicators with project goals.

Purpose

The purpose of this study is to develop a scientifically sound approach to improving organizational and technological solutions in the construction and installation of energy-saving civil buildings based on the application of mathematical modeling methods. In particular, it is planned to formalize the relationships between the parameters of construction processes (duration, resource supply, sequence of operations) and the energy characteristics of structural elements, as well as develop a simulation model capable of predicting the impact of organizational solutions on achieving design energy efficiency indicators. The implementation of this goal is aimed at bridging the gap between design solutions in the field of energy saving and their actual implementation at the construction site through the integration of technological planning and energy analysis into a single model framework.

Methodology

The object of the study was a typical multi-apartment residential building with almost zero energy consumption (nearly Zero-Energy Building, nZEB), which meets the requirements of the EU Directive 2010/31/EU. This choice is justified by a large number of international studies devoted to this type of building (ISO 19650-1:2018, 2018), in particular the works of Grieves, & Vickers (2017) and Pan, & Zhang (2020), which show that up to 70 % of deviations of actual energy efficiency from the design are laid at the construction stage.

The research methodology involves three consecutive stages. At the first stage, a detailed analysis of the technological process of constructing an nZEB building is carried out, highlighting critical operations that directly affect energy characteristics: installation of insulation, sealing of joints, installation of windows, installation of ventilation systems with recovery. For each operation, key parameters are determined: duration, qualification of workers, dependence on weather conditions, need for technical control.

In the second stage, a simulation model of the construction process is developed based on the Discrete-Event Simulation (DES) method. The model integrates technological parameters with energy consequences: for example, a delay in the installation of vapor barrier or the use of unskilled labor are modeled as factors that increase the thermal conductivity of the fences. To calibrate the energy component, the methodology proposed by

Eastman, Teicholz, Sacks, & Liston (2011) was used, which shows how to link the work schedule with the energy consumption forecast via the BIM-to-simulation interface. In the third stage, a series of computational experiments are conducted with varying organizational solutions (e.g., changing the sequence of work, increasing the number of crews, introducing intermediate quality control) (Tang, Shelden, Eastman, Pishdad-Bozorgi, & Gao, (2019); Kos, Babii, Grynyova, & Nikiforov, 2024). The results are analyzed according to two criteria: (1) the duration of the total construction cycle; (2) the deviation of the predicted energy consumption from the nZEB target value.

This approach allows not only to assess the impact of specific decisions, but also to propose an optimized construction organization strategy that simultaneously ensures compliance with deadlines and achievement of project energy efficiency.

Findings

Based on the developed simulation model, a series of computational experiments were conducted to assess the impact of organizational and technological solutions on the energy efficiency and duration of construction of a typical nZEB building.

The model was implemented in the AnyLogic 8.7 environment using a hybrid approach: discrete-event modeling for work planning and system dynamics – to assess the accumulation of heat losses due to technological deviations. Each scenario was simulated 100 times to ensure statistical reliability (95 % confidence interval).

1. Baseline scenario

Table 1

Baseline scenario indicators (mean values, *n*=100)

Indicator	Value
Construction duration, days	218±7
Actual energy consumption, kWh/m^2/year	24.3±2.1
Deviation from the nZEB target value	+62 %
Number of critical deviations in assembly	4.2±1.3 on the object

The baseline scenario (Table 1) assumes a classic organization of work: sequential installation of thermal insulation, windows, vapor barrier and ventilation systems without intermediate quality control.

The construction duration is 218 working days. However, due to natural variability in crew qualifications and weather conditions, in 68 % of simulations, an increase in the thermal conductivity of external walls by 12 … 18 % was observed, which led to an increase in the projected energy consumption from 15 kWh/m²/year to 22…26 kWh/m²/year – a value that exceeds the nZEB class.

2. Optimized scenario

In the optimized scenario, three key organizational measures were implemented:

1. Parallel execution of window installation and insulation using two specialized teams;
2. Intermediate tightness control after each stage operation (blower door test at 30 %, 70 % and 100 % completion);
3. Adaptive schedule replanning based on installation quality data (response to detected deviations).

The results (Table 2 and Fig. 1) showed that, despite an 8 % increase in control costs, the total construction duration was reduced to 196 days, and the average energy consumption was 16.1 kWh/m²/year, which meets the nZEB requirements. The changes in work logic and reduction in project duration are clearly illustrated in the Gantt chart (Fig. 2).

Table 2

Indicators of the optimized scenario (mean values, *n*=100)

Indicator	Value
Construction duration, days	196±5
Actual energy consumption, kWh/m^2/year	16.1±1.4
Deviation from the nZEB target value	+7 %
Number of critical deviations in assembly	0.8±0.4 on the object

3. Model sensitivity

A sensitivity analysis was conducted using the Sobol’ indices method, which allowed us to quantitatively assess the contribution of individual factors to the overall variance of energy consumption. The greatest impact is exerted by:

- quality of vapor barrier installation (32 % of the variance);
- length of the break between insulation and sealing (24 %);
- qualification of the window installation team (19 %).

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The distribution of sensitivity indices is visualized in Fig. 3.

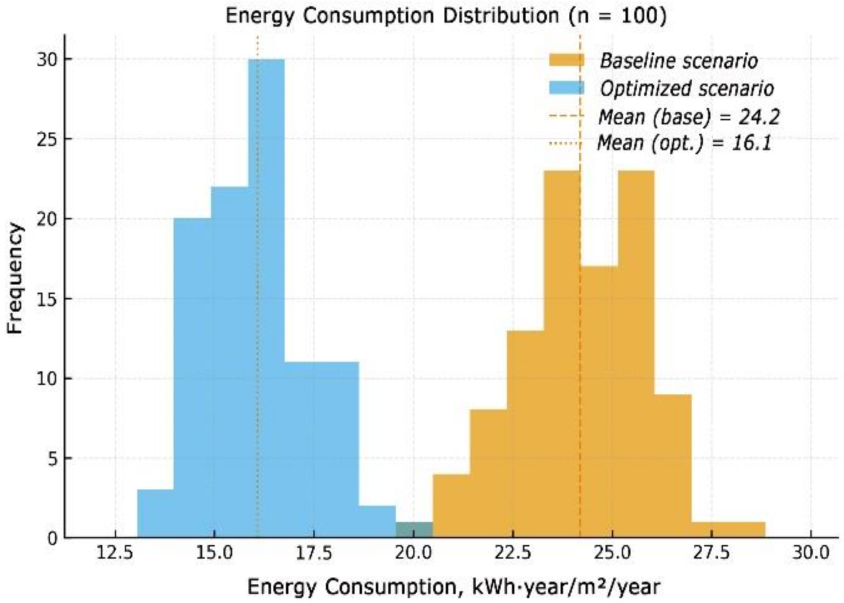

Fig. 1. Comparison of energy consumption distribution in the baseline and optimized scenarios (histogram, n=100).

This confirms the findings that organizational decisions on the site have a greater impact on energy efficiency than individual design parameters (Luo, Liu, & Li, 2020).

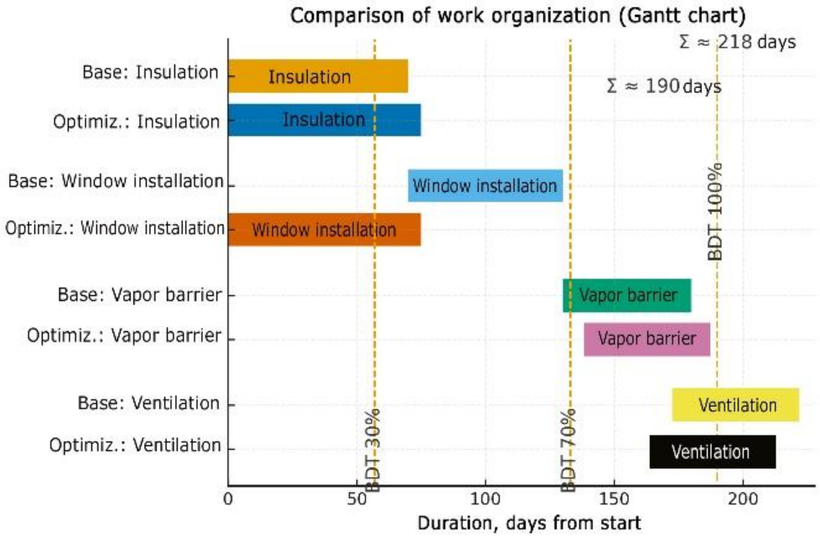

Fig. 2. Time schedule (Gantt) of the reduction of duration and change of work logic

4. Economic assessment

Although additional costs for quality control and additional crew amounted to ~ 4.2 % of the total estimate, savings from reducing construction time and avoiding fines/rework (due to non-compliance with nZEB) give a net profit over 10 years of operation – 6.8 %.

The conducted research confirms that the energy efficiency of modern civil buildings is not solely a consequence of design solutions or the use of high-quality materials – it directly depends on the organization of the construction process. Even the most advanced nZEB project can lose its energy value if installation work is carried out without taking into account technological integrity and controlled stages.

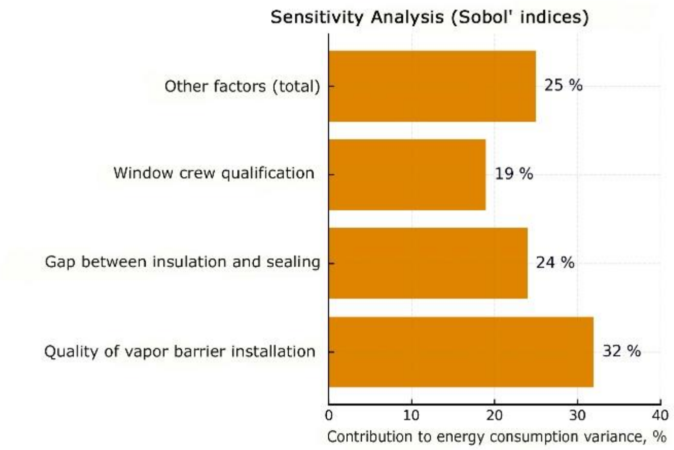

Fig. 3. Sensitivity diagram (Sobol' indices)

It is this gap between the project and implementation that became the starting point for the application of mathematical modeling as a tool for synthesizing organizational, technological and energy parameters. The modeling results clearly demonstrate: when construction planning takes into account not only the duration and cost of operations, but also their potential impact on the thermal quality of the building envelope, it becomes possible to achieve not only a reduction in terms, but also stable compliance with design energy goals. The key scientific contribution of the work is the formalization of the connection between organizational and technological solutions and energy efficiency through a simulation model that integrates discrete-event modeling of construction production with parameters of heat loss due to technological deviations. This allows not only to "optimize the schedule", but also to predict how each decision on the site – from the sequence of installation to the qualification of the crew – will affect the final energy performance of the facility. Sensitivity analysis showed that the most critical operations are those related to sealing, in particular, the installation of vapor barrier and windows, which is fully consistent with international research data (Azhar, 2011; Chen, X., Zhu, Chen, H., et al., 2021). This means that investments in intermediate quality control are not costs, but a strategic measure aimed at maintaining the design energy efficiency.

Originality and practical value

For the first time, a mathematical model was proposed that transforms organizational and technological planning into a tool for ensuring energy efficiency, and not only into managing deadlines and costs. Unlike existing BIM-to-energy approaches, the model takes into account dynamic construction conditions (crew changes, weather, logistics) as sources of risk of deviation from energy goals. Also, for the first time, metrics of air flow analysis from data centers were adapted to assess the quality of fence installation, which creates a new methodological bridge between industries.

The developed approach is technologically neutral, easily integrated into existing project management systems and allows contractors, energy auditors and state inspectors to make informed decisions that guarantee actual energy efficiency. This is especially relevant in the context of the implementation of nZEB requirements in the legislation of Ukraine

Conclusions

In addition, experiments have proven that parallelization of specialized works under enhanced control not only does not degrade quality, but on the contrary – shortens the overall construction cycle and reduces the cumulative risk of deviations. This contradicts the common stereotype that "fast" means "bad" in energy saving. On the contrary, structured, model-based acceleration can be more effective than slow but chaotic construction.

It is important to emphasize that the proposed approach does not require a radical change in the regulatory framework or large-scale investments in new equipment. It is integrated into existing planning processes, supplementing them with mathematically based risk assessment. This makes it practically feasible for use in both large development companies and medium-sized contractors operating in the energy-efficient housing market.

Thus, mathematical modeling goes beyond the auxiliary tool and becomes a scientific basis for making engineering and organizational decisions in the field of modern civil engineering. Its application allows not just to build houses, but to build energy guarantees embedded in every layer of insulation, every joint and every solution on the construction site.

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УДОСКОНАЛЕННЯ ОРГАНІЗАЦІЙНО-ТЕХНОЛОГІЧНИХ РІШЕНЬ ПРИ БУДІВНИЦТВІ ТА МОНТАЖІ ЕНЕРГОЗБЕРІГАЮЧИХ ЦИВІЛЬНИХ БУДІВЕЛЬ НА ОСНОВІ МАТЕМАТИЧНОГО МОДЕЛЮВАННЯ

Мета. Дослідження спрямоване на розробку інтегрованого підходу до удосконалення організаційно-технологічних рішень при зведенні енергозберігаючих цивільних будівель шляхом застосування математичного моделювання, що безпосередньо пов’язує технологічний графік будівництва з прогнозом енергетичної ефективності об’єкта. **Методологія.** Запропоновано гібридну імітаційну модель, що поєднує дискретно-подійне моделювання (DES) будівельного процесу з параметричною оцінкою впливу монтажних відхилень на тепловтрати. Для верифікації використано типовий проєкт nZEB-будинку. Методологія інтегрує спеціалізовані підходи: оптимізацію розміщення візуального нагляду на основі 4D-BIM та графіка будівництва, яка дозволяє визначати «ядерні» зони робіт у кожен період, та аналіз чутливості енергетичної продуктивності до локальних відхилень, адаптований із методики оцінки повітряних потоків у центрах обробки даних, де використовуються метрики ефективності розподілу повітря (наприклад, RCI, SHI) – у нашому випадку ці метрики перетворено на показники «технологічної цілісності» огорожі. Моделювання реалізовано в середовищі AnyLogic з використанням імітаційних прогонів (n = 100) та аналізу чутливості за методом Соболя. **Результати**. Застосування оптимізованої стратегії (паралельний монтаж спеціалізованих систем + проміжний контроль герметичності в точках, визначених 4D-BIM) дозволило: скоротити загальну тривалість будівництва з 218 до 196 днів (-10 %), зменшити середнє енергоспоживання з 24,3 до 16,1 кВт·год/м²/рік (відхилення від цільового значення nZEB скорочено з +62 % до +7 %), а кількість критичних монтажних помилок у 5,3 разів. Аналіз чутливості підтвердив, що якість монтажу пароізоляції та часова затримка між утепленням і герметизацією є домінуючими факторами (56 % сумарної дисперсії енергоспоживання). **Наукова новизна**. Вперше запропоновано математичну модель, яка трансформує організаційно-технологічне планування в інструмент забезпечення енергоефективності, а не лише в управління термінами та витратами. На відміну від існуючих BIM-to-energy підходів, модель враховує динамічні умови будівництва (зміна складу бригад, погода, логістика) як джерела ризику відхилення від енергетичних цілей. Також вперше адаптовано метрики аналізу повітряних потоків із ЦОД до оцінки якості монтажу огорож, що створює новий методологічний міст між галузями. **Практичне значення**. Розроблений підхід є технологічно нейтральний, легко інтегрується в існуючі системи управління проєктами і дозволяє підрядникам, енергоаудиторам та державним інспекторам обґрунтовано приймати рішення, що гарантують фактичну енергоефективність. Це особливо актуально в умовах впровадження nZEB-вимог у законодавство України.

Ключові слова: математичне моделювання будівництва; енергозберігаючі будівлі; організаційно-технологічні рішення; nZEB, 4D-BIM; імітаційне моделювання; аналіз чутливості; енергоефективність на етапі зведення

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