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OPTIMIZATION OF THE CONFIGURATION OF PREFABRICATED ELEMENTS FOR THE RAPID ASSEMBLY OF LOW-RISE BUILDINGS

The article investigates the complex problem of optimizing the configuration and logistics of prefabricated elements used for the rapid assembly of low-rise buildings (in particular, using modular and prefab construction technologies). The relevance of the topic is determined by the need to accelerate the pace of construction of residential and infrastructure buildings in the context of Ukraine's post-war reconstruction, as well as global trends in the transition to industrial construction methods. The essence and differences of the concepts of "modular construction" and "prefab structures" are analyzed, and their key advantages over traditional construction methods are highlighted.

Special attention is paid to the logistics aspect, as transportation costs can account for up to 35% of the total estimated cost of construction. The paper presents calculations of the weighted average transport distance and a comparative analysis of pendulum, circular, and one-way transport schemes. It is proved that the choice of an optimal supply scheme from the manufacturing plant (for example, a plant of reinforced concrete or metal structures) directly to the construction site can reduce transportation costs by more than 40%.

The article presents a comparative analysis of the Life Cycle Cost (LCC) of traditional and innovative (energy-efficient) modular buildings, confirming the long-term economic benefits of the optimized configuration of high-tech prefabricated elements. Recommendations are developed for organizing rhythmic construction flows (with a step of 1-3 days) to ensure continuous and efficient assembly. The study results are of high practical significance for contractors, developers, and logistics operators seeking to minimize costs and shorten construction times while maintaining the highest levels of quality and safety.

Keywords: *modular construction, prefab structures, construction logistics, technologies, construction logistics, transport schemes, rapid assembly, BIM technologies, energy efficiency, logistics, modular construction, quality, digitalization, digital transformation, construction parameters, resource management, resource and logistics support, construction organization, organizational and technological model, life cycle cost.*

Introduction. The dynamic development of science and technology, as well as the need for prompt resolution of socio-economic challenges, contribute to the introduction of modern efficient structures in the construction industry [8]. The search for ways to accelerate the construction of buildings is a leading issue in the construction industry of Ukraine, which is particularly acute in the conditions of martial law, large-scale destruction of the housing stock, and the need to provide internally displaced persons with temporary and permanent housing [3, 6].

Traditional construction methods, although providing high indicators of reliability and durability, are significantly inferior to industrial (modular and prefabricated) technologies in terms of speed, resource efficiency, and cost optimization [6]. Transforming the construction site into an assembly site, where structures with a high degree of factory readiness (up to 90%) are assembled, allows for a radical change in the approach to organizing construction production [6, 8]. In this context, optimizing the configuration of prefabricated elements and managing transport and logistics flows becomes a key success factor. Logistics and efficient supply directly affect the total estimated cost of the facility, as transportation costs can account for a significant portion of the budget [2].

Relevance is determined by the need to accelerate the construction of residential and infrastructure facilities in the context of Ukraine's post-war reconstruction and the global shift toward industrial construction methods (modular and prefabricated technologies). The topic is also актуальна because logistics directly affects overall project cost and schedule; transportation expenses may form a significant share of the construction budget, and inefficient supply schemes lead to additional costs and delays.

Problem statement. The purpose of the article is to develop a comprehensive approach to optimizing the configuration and supply of prefabricated elements to ensure the rapid assembly of low-rise buildings. To achieve this goal, the following tasks are solved: classification of prefabricated modular systems, determination and calculation of optimal transport and logistics schemes and BIM technologies into the assembly control process, and evaluation of the economic efficiency of this approach by calculating the life cycle cost (LCC).

Analysis of recent research and publications. The issues of modular construction, logistics optimization, and the introduction of innovations in construction are widely covered in the works of domestic and foreign scientists. D.O. Khokhriakova provides a thorough analysis of terminology, distinguishing between the concepts of "prefab" (flat panel systems) and "modular construction" (volumetric block systems) [8]. M.V. Kinailiuk investigates the historical aspect and advantages of modular construction on the example of hotels, emphasizing the reduction of construction time to 45 days and a 30% reduction in costs [4].

The issues of logistics support for construction, in particular the role of transport infrastructure and supply schemes, are addressed in the works of T.V. Dedilova, O.V. Yurchenko, and their co-authors [2, 9]. They prove that a rational choice between pendulum, circular, or one-way traffic schemes significantly affects the total estimated cost of the project [9]. O.V. Semykina, I.V. Zadorozhnikova, and others study the structural features of modern modular buildings, in particular the types of connections (inter-modular, intra-modular) and types of frames [3].

The integration of modern digital tools, such as the use of UAVs (drones) for logistics and control using BIM models, is considered in the studies of S.V. Leonova, N.R. Basarab, and L.V. Rudnyk [5]. At the same time, economic aspects, life cycle cost (LCC) management, and the concept of positive energy balance (Energy+) buildings are disclosed in the works of I.I. Perehinets [7]. Despite the significant number of publications, the synergy of transport optimization, configuration of prefabricated elements, and digital monitoring at the stage of assembling low-rise buildings requires further comprehensive research.

The purpose of the article is to develop a comprehensive approach to optimizing the configuration and supply of prefabricated elements to ensure the rapid assembly of low-rise buildings. This includes classifying prefabricated/modular systems, determining and calculating optimal transport and logistics schemes and BIM technologies into assembly control, and evaluating economic efficiency through Life Cycle Cost (LCC) assessment.

The scientific novelty of the proposed approach lies in defining information alignment as the central variable that determines the magnitude of coordination losses and the overall efficiency of construction production. Advancing this approach makes it possible to establish a unified information-and-management environment that synchronizes design, production, logistics, and on-site execution, thereby ensuring the continuity of flow-based construction and enabling high-speed delivery of low-rise and industrial building projects.

Main material presentation. For effective configuration optimization, it is first necessary to clearly classify building elements. According to studies, it is advisable to distinguish between "prefab structures" (mostly two-dimensional flat panel systems) and "modules" (three-dimensional autonomous volumetric elements) [8]. Volumetric modules provide up to 60-90% factory readiness [8].

Modern modular buildings are classified by their structural scheme: a scheme with a stiffening core, a scheme with load-bearing walls, a scheme with corner support columns, and an external frame [3]. For low-rise buildings (up to 5 floors), the most rational is the block scheme with continuous stacking of blocks, which allows all interior finishing operations and the laying of engineering networks to be transferred to factory conditions [6]. Completely finished units are delivered to the construction site, requiring only the arrangement of joints (inter-modular connections by welding or using bolts/connectors) [3 ,6].

Transportation costs, integrated into the total estimated cost, can account for up to 35% of the overall project budget [2]. Accordingly, the logistics support of the configuration requires a detailed technical and economic analysis. The choice of the optimal supplier is based not only on the price of the material but also on the weighted average road transport distance (*Law*), which is calculated using formula (1) [2]:

$$L_{aw} = \frac{\sum_{i=1}^{n} Q_i \times L_i}{\sum_{i=1}^{n} Q_i} \quad (1)$$

where: *Law* — weighted average transport distance, km; *Li* — distance from supplier *i* to the construction site, km; *Qi* — quantity of building materials (modules) transported from point *i*, tons; *n* — number of suppliers [2].

The choice of a transport scheme is critical. Pendulum, circular, and one-way schemes are distinguished [9]. The pendulum scheme (a radial round-trip route) has a low coefficient of useful work if the transport returns empty [9]. The circular scheme is effective when serving several sites but faces a decrease in load capacity after each unloading [9].

Using the example of supplying 5 infrastructure facilities (total volume of 101.8 thousand tons of materials), three supply schemes are considered:

- Scheme 1: From the building materials warehouse.
- Scheme 2: From the railway point.
- Scheme 3: Directly from the precast concrete (PC) plant or module factory

Table 1

Comparative analysis of transport costs using different logistics schemes [2]

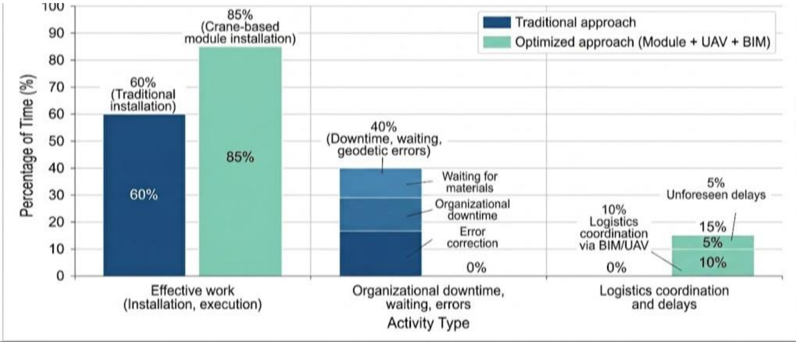
Transportation Scheme	Weighted average distance, km	Transportation volume, tons	Cost per 1 t-km, UAH	Total transport costs, thousand UAH	Savings relative to Scheme 1, %
Scheme 1 (From warehouse)	15.82	101.8	45	72.461	-
Scheme 2 (From railway)	11.70	101.8	45	53.596	26.0%
Scheme 3 (From plant)	9.28	101.8	45	42.516	41.3%

As can be seen from Table 1, supplying prefabricated elements directly from the manufacturer (Scheme 3) reduces costs by more than 41.3% [2]. This confirms that for rapid assembly, it is best to configure facilities directly from the factory, bypassing intermediate warehouses, according to the "just-in-time" principle.

Classical logistics is insufficient for optimizing assembly on the construction site. The integration of Building Information Modeling (BIM) is becoming a key element [5]. The use of drones equipped with real-time kinematic (RTK) systems provides spatial triangulation with centimeter accuracy [5]. Drones can scan the site and transmit data to the BIM platform, allowing contractors to:

1. See the actual position of prefabricated elements and prefabricated foundations.
2. Adjust construction plans "on the fly" if deviations from the project are detected.
3. Track the movement of goods and vehicles in real-time, optimizing access roads for large modules.

In addition, UAVs can be used for the express delivery of small components (fasteners, connectors, tools) weighing up to 5 kg with a readiness and speed (about 7 minutes per flight) that is unattainable for ground transport in traffic jam conditions [5].



Graph 1. Dynamics of working time utilization on the construction site under traditional and optimized (Module + UAV + BIM) approaches.

The construction of buildings using modular technology is carried out by flow methods. The work front is divided into areas and sections (for example, one floor or section) [6]. The optimal rhythm of the flow in volumetric-block housing construction is 1-3 days [6]. A specialized assembly flow is formed from 3 partial flows:

1. Assembly of volumetric blocks (installation into the design position).
2. Monolithic sealing, welding of connectors, and sealing of joints.
3. Connection of engineering communications (plumbing, electrical) in specially provided shafts [6]. Thanks to factory readiness, there is no need for lengthy plastering, painting, and electrical work on site [6]. The duration of building construction is reduced significantly (e.g., a hotel can be assembled in 45 days) [4]).

Rapid assembly and high-tech configuration require significant initial investments (15-30% higher than traditional methods) [7]. However, economic feasibility should be evaluated by the criterion of Life Cycle Cost (LCC) over a 100-year horizon.

Formula for calculating the life cycle cost [7]:

$$LCC = C_b + C_m + C_u + C_{rep} - I_e - V_{res} \quad (2)$$

where *Cb* — construction costs; *Cm* — maintenance and repair costs; *Cu* — utility/insurance payments; *Crep* — equipment replacement (e.g., solar power plant); *Ie* — income from energy sales (for Energy+ buildings); *Vres* — residual value.

Table 2

Comparison of the life cycle cost (100 years) of a modular house (Energy+) and a traditional house [7]

Indicator	Class A House (Modular Energy+)	Class C House (Traditional)
Construction cost, $	165,000	130,000
Specific energy consumption, kWh/m²/year	30	100
Repair costs for 100 years, $	731,548	288,185
Energy consumption costs, $	0	576,371
Income from energy sales (SPP), $	-738,198	0
Residual asset value, $	1,949,263	0 (disposal costs 230,367)
Total LCC (adjusted for inflation), $	-1,083,930 (profit)	1,756,958 (costs)

These calculations prove that the use of modern modular systems, equipped with energy-efficient elements (solar panels, heat exchangers), not only accelerates assembly but also turns the building into a profitable asset [1]. Thanks to serial production and unification (applying the "commodity unit" principle), design costs are minimized [1].

Conclusions. The conducted research confirms that optimizing the configuration of prefabricated elements for the rapid assembly of low-rise buildings requires a synergistic approach. First, the transition from traditional methods to the use of factory-ready 3D modules ensures a radical reduction in construction time (building construction in 45-120 days) and independence from weather conditions. Second, the optimization of logistics processes is critical. It has been proven that direct supply from the manufacturer via a one-way or optimized circular scheme reduces transportation costs by 41.3% compared to complex warehouse logistics. Third, modern assembly is impossible without digitalization. The use of UAVs in conjunction with BIM models allows for topographic control with RTK accuracy down to a centimeter, real-time supply tracking, and avoidance of downtime. Despite the higher initial cost of quality prefabricated structures, Life Cycle Cost (LCC) analysis confirms the absolute economic viability of this approach in the long term. The proposed configuration and logistics model can serve as a reliable basis for large-scale post-war reconstruction programs in Ukraine and the development of commercial and social infrastructure.

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Оптимізація конфігурації збірних елементів для швидкого збирання малоповерхових будівель

У статті досліджується комплексна проблематика оптимізації процесів комплектації та логістичного забезпечення збірних елементів, що використовуються для швидкого монтажу об’єктів малоповерхової забудови (зокрема, за технологіями модульного та prefab-будівництва). Актуальність теми зумовлена необхідністю пришвидшення темпів зведення житлових та інфраструктурних будівель в умовах повоєнної відбудови України, а також глобальними тенденціями переходу до індустріальних методів будівництва. Проаналізовано сутність та відмінності понять «модульне будівництво» та «prefab-конструкції», виділено їхні ключові переваги над традиційними методами зведення.

Особлива увага приділяється логістичному аспекту, оскільки транспортні витрати можуть становити до 35% від загальної кошторисної вартості будівництва. У роботі наведено розрахунки середньозваженої відстані перевезень та порівняльний аналіз маятникової, кільцевої та односторонньої транспортних схем. Доведено, що вибір оптимальної схеми постачання від заводу-виробника (наприклад, заводу залізобетонних або металевих конструкцій) безпосередньо до будівельного майданчика дозволяє знизити транспортні витрати більш ніж на 40%.

В статті наведено порівняльний аналіз вартості життєвого циклу (LCC) традиційних та інноваційних (енергоефективних) модульних будівель, що підтверджує довгострокову економічну вигоду від оптимізованої комплектації високотехнологічних збірних елементів. Розроблено рекомендації щодо організації ритмічних будівельних потоків (із кроком 1-3 доби) для забезпечення безперервного та ефективного монтажу. Результати дослідження мають високу практичну значущість для підрядних організацій, девелоперів та логістичних операторів, які прагнуть мінімізувати витрати та скоротити терміни зведення об'єктів.

Ключові слова: *модульне будівництво, збірні конструкції, логістика будівництва, транспортні схеми, швидкий монтаж, BIM-технології, енергоефективність, логістика, модульне будівництво, якість, цифровізація, цифрова трансформація, параметри будівництва, управління ресурсами, ресурсно-логістичне забезпечення, організація будівництва, організаційно-технологічна модель, вартість життєвого циклу.*