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RESEARCH OF INDUSTRIAL BUILDING DESIGN METHODS

Abstract. *The article presents a comparative analysis of modern methods for designing industrial buildings in Germany, Japan, the United States, and China, and assesses the applicability of the identified practices to the conditions of Kazakhstan. The main areas of research include Building Information Modeling (BIM), modular (prefabricated) construction, energy-efficient and low-carbon technologies, as well as methods for improving seismic resistance. Methodologically, the study is based on a systematic review of scientific literature and industry reports from 2018 to 2025, a regulatory analysis, and a comparison of implemented projects - with a particular focus on quantitative indicators such as time reduction, waste minimization, and lower energy consumption. The results show that the integration of BIM and modular technologies significantly reduces design clashes and operational inefficiencies, provided there is a developed manufacturing base and module standardization. Energy-efficient solutions - such as enhanced building envelopes, heat recovery systems, and the use of renewable energy sources - make it possible to reduce the energy consumption of industrial complexes by 20–50%, depending on the applied technologies and the initial condition of the facility. Seismic isolation and damping systems decrease transmitted accelerations and help maintain equipment functionality in seismically active regions. For Kazakhstan, a phased adaptation strategy is proposed: pilot implementation of BIM in public sector projects, the development of local prefabrication facilities, the introduction of stricter energy standards for industrial envelopes, and the targeted application of seismic protection for critical facilities. The conclusion presents practical recommendations on regulatory support, human resource development, and directions for future quantitative research.*

Keywords: *industrial construction, BIM, modular structures, energy efficiency, seismic resistance, Kazakhstan*

Introduction. Industrial buildings play a key role in the infrastructure of the national economy, forming the spatial basis for production, storage, and distribution of material resources. Contemporary requirements for industrial facilities include not only ensuring technological suitability and safety, but also aspects of energy efficiency, environmental performance, adaptability to changing production tasks, and resilience to natural hazards. In the context of globalization and tightening environmental constraints, a number of developed countries over recent decades have developed and implemented design and construction methods that significantly increase project efficiency: Building Information Modeling (BIM), modular prefabrication, application of “green” technologies, and seismic protection systems [1].

In recent decades, publications on industrial buildings have concentrated around several directions. Building Information Modeling is considered as an instrument for coordinating engineering disciplines, allowing a reduction in the number of clashes, improved estimate accuracy, and ensuring data transfer to the operational phase. Numerous studies demonstrate a reduction in on-site errors when BIM processes are systematically used. The United States focuses on integration of BIM with facility management and on broad deployment of renewable energy sources in the industrial sector [6].

In energy management, the main emphasis is placed on combining enhanced thermal insulation of envelopes, heat-recovery ventilation systems, and integration of renewable energy sources, while assessing sustainability and economic feasibility by employing LCA and LCCA methods. Germany demonstrates successful practices of industrialized construction with a high share of factory assembly and strict energy standards [8].

Prefabrication and modular construction are studied as means to accelerate erection, improve factory quality, and reduce construction waste; practices in several countries demonstrate that, given established logistics and module standardization, significant reductions in project delivery times are achievable. China, by stimulating mass adoption of prefabrication and standardization, shows examples of rapid scaling of production and shortened commissioning times [2].

With regard to seismic resistance and durability, foreign developments confirm the effectiveness of performance-based approaches and active measures to reduce transmitted accelerations, such as base isolation and damping systems. Japan stands out with innovations in seismic protection and renovation of buildings under the “near-zero energy building” (ZEB) concept [11].

Kazakhstan possesses significant industrial otential but faces a number of challenges: a continental climate with sharp seasonal temperature swings, dispersion of industrial sites across a large territory, limited digital maturity of design organizations, and the need to update the regulatory framework. These circumstances make it pertinent to study foreign experience to correctly adapt it to national conditions. The aim of this work is to systematize design methods for industrial buildings, assess their effectiveness, and propose practical recommendations for adaptation and phased deployment in Kazakhstan. To achieve this aim, the study solves the following tasks: analysis of the state of BIM and digitalization in leading countries; assessment of advantages and limitations of modular prefabrication; examination of energy-efficient solutions and seismic protection technologies; comparison of foreign practices with Kazakh realities; and formulation of recommendations for practice and policy.

Literature review. Contemporary research confirms that methods for designing industrial buildings concentrate on four directions: digitalization of design processes (BIM), industrialization of construction, enhancement of energy efficiency, and implementation of seismic protection solutions. BIM enables comprehensive lifecycle management of a building, improving coordination of design decisions and reducing the number of constructionstage errors [6]. These technologies have proven effective given regulatory support and the training of specialists capable of implementing and maintaining digital models.

Modular and prefabricated construction is considered a primary tool for accelerated industrialization and cost reduction in the construction industry. Studies indicate that the application of modular technologies can reduce construction time by 30-50% and decrease construction waste volumes by up to 90% [1]. Foreign examples - notably projects by Goldbeck in Germany and Takenaka in Japan - demonstrate consistent improvements in energy performance and quality thanks to standardization and factory assembly.

In the field of energy efficiency, emphasis is placed on integrating energy-saving technologies, heat recovery systems, and renewable energy sources. The experience of implementing Net-Zero Energy Building (ZEB) projects and BREEAM-certified developments confirms the potential to reduce industrial energy consumption by 20-70% depending on baseline conditions and depth of interventions [11]. The most effective solutions are those based on comprehensive lifecycle assessment and operational monitoring.

In countries with elevated seismic activity, wide adoption has been seen of base isolation, damping devices, and “seismic-resilient” design concepts that substantially reduce energy transmitted to structures and equipment [9]. For industrial facilities, this is especially important: destruction or displacement of technological equipment can lead to production stoppages and environmental incidents. Application of base isolation and dampers in criticalobject projects has shown reductions in seismic accelerations to one-third–one-fifth of original values and substantial savings on postevent recovery.

Kazakhstan is endowed with industrial potential but faces specific challenges: continental climate, seismically active regions (notably in the south and southeast), wide territorial dispersion of industrial assets, and limited digital maturity in design organizations. These factors determine the need for a country-specific adaptation path that accounts for climatic zoning, logistics, and normative modernization. A stepped strategy is required, starting with pilot BIM projects, localizing prefabrication production, tightening thermal standards for industrial envelopes, and targeted application of seismic protection for critical infrastructure.

Materials and methods. The study is based on a combined analysis: a systematic review of scientific literature and industry reports (Scopus, Web of Science, Google Scholar, NREL repositories, corporate publications and professional associations), analysis of regulatory acts and technical guidelines (European and national standards), as well as examination of practical case studies documented in reports and publications for 2018-2025. The initial search included approximately 420 materials; after screening and critical quality assessment, 15 highquality sources were included in the main analysis.

Selection criteria included studies and reports containing objective empirical data or detailed project descriptions: indicators of construction time reduction, material savings, decreased energy consumption, descriptions of seismic protection technologies, and documents revealing regulatory features of BIM and prefabrication implementation. Publications with low evidence levels and articles without practical illustrations were excluded.

The following methods were used:

- qualitative comparative analysis for juxtaposing practices across countries;
- aggregation of quantitative indicators (percentage reductions in time/costs/energy consumption) from systematized reviews and technical reports;
- regulatory analysis to identify barriers and incentives. Additionally, a simple technoeconomic model (appendix) was employed to illustrate the economics of a miniplant producing sandwich panels (calculations of CAPEX, OPEX, cash flow, payback, and NPV under several scenarios). All assumptions and input parameters used in the model are described in the text and in the model appendix (see methodology).

Limitations of the study arise from the quality and comparability of sources: differing methodologies for measuring effects across countries and projects complicate direct statistical comparisons. Nevertheless, the combination of qualitative synthesis and illustrative quantitative examples allows the formulation of practical recommendations for pilot implementation in Kazakhstan.

Results and discussion. BIM - Opportunities, Impacts and Barriers to Implementation. BIM (Building Information Modeling) is evolving toward full lifecycle management of assets: design (3D), scheduling (4D), cost estimation (5D), and facility management (6D). International experience shows that BIM adoption, when coordinated among project participants, reduces the number of clashes on construction sites, decreases the volume of rework, and saves time. According to several studies, BIM implementation can reduce errors and rework during construction by an average of 20-40%, increase the productivity of design teams, and lower the overall cost of corrections [7]. In Germany and the UK, mandatory or incentive-based BIM policies by governments have led to market development and the emergence of qualified BIM managers. [4]. China and Japan have used public programs to stimulate BIM adoption with focuses on industrialization and lifecycle management respectively [5].

Figure 1 shows the growth in BIM investments from 2020, with an upward trend projected through 2030. This indicates that construction companies are progressively adopting and expanding their use of BIM in project design, underscoring that BIM represents the future of the industry.

BIM is no longer solely a technology for modelling three-dimensional geometry: it has become a means of organizing the design process, managing data quality, and ensuring continuity of information from design through construction and into operation. BIM implementation requires not only software, but also process reorganization - defining responsibilities, standards for levels of model detail, exchange formats, and validation rules.

In industrial construction, BIM enhances transparency of interactions between architects, structural engineers, MEP engineers and contractors, which is critical when working with complex technological lines and high levels of engineering intensity within premises. A key aspect is integration of the model into operational processes, where the digital twin serves as a source of data for maintenance planning, spare-parts accounting, and energy consumption analysis.

Figure 1 – BIM funding volumesv

In Kazakhstan, regulatory initiatives for BIM implementation have already started for complex projects; however, the digital maturity of the industry remains low: there is a shortage of professional personnel, lack of unified methodologies, and limited integration of BIM into operation [12]. These barriers can be overcome with a phased strategy: piloting BIM on public projects, creating educational programs in collaboration with universities and industry centers, developing national data exchange templates (compliant with ISO 19650), establishing certification mechanisms for BIM managers, and introducing incentives for contractors.

Modular (Prefabricated) Construction - Time, Quality and Resource Savings. Modular prefabrication implies the production of building components and elements in factory conditions with subsequent on-site assembly. Key advantages are quality control, independence from weather conditions, and compressed installation schedules. Reviews indicate that modular technologies reduce erection times by 30–50% and lower construction waste by 60-90% depending on the type of elements and the level of factory assembly [1]. In Germany (e.g., Goldbeck) and China, scaling of prefabrication projects has been achieved through standardization, industrial production, and efficient logistics [8]. For industrial facilities, fully tested MEP modules (mechanical, electrical, and plumbing units), envelope panels, and blocks for temporary or permanent personnel accommodation are particularly valuable.

The shift toward industrialized construction means transferring a significant portion of work to factory conditions. Prefabrication ensures standardized nodes, high repeatability of quality, and reduced dependence on site weather. In the industrial context, factory assembly practices cover frame elements, façade and roof panels, as well as complete MEP modules that are fully tested before installation. A major advantage is the opportunity to test engineering systems in production conditions, which significantly reduces the number of commissioning errors. However, effective prefabrication requires well-thought logistics, coordination of design interfaces, and standardization of geometric parameters of modules. Economically, success depends on stable demand, optimization of production lines, and proximity to markets. For a territorially large state like Kazakhstan, localized mini-production facilities are more resilient than centralized factories subject to long transport times.

The level of funding for modular construction is shown in Figure 2

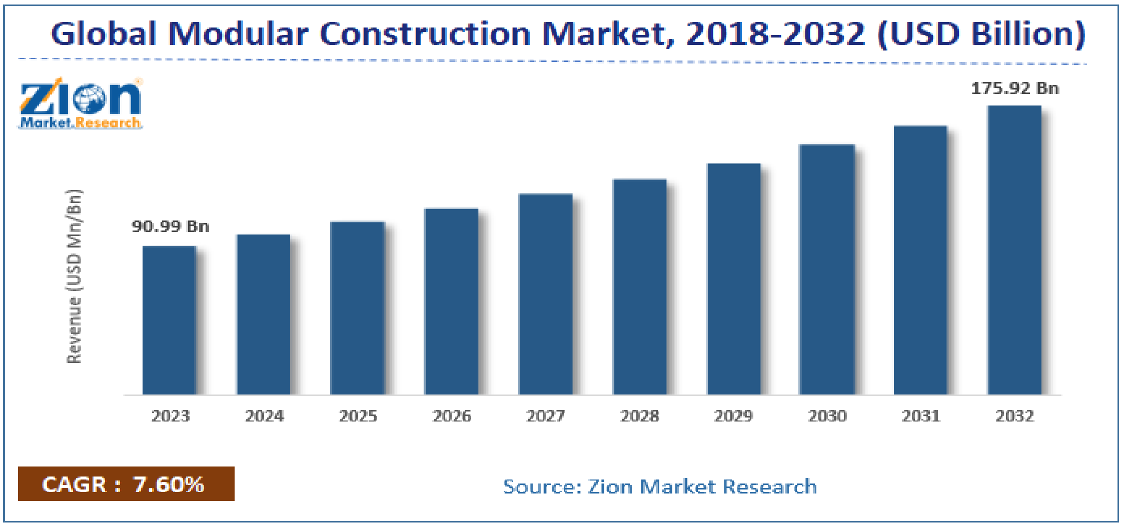

Figure 2 - Financing levels in modular construction

Limitations include initial capital costs for organizing factory production, the necessity to load base manufacturing capacity, and standardization of module interfaces. For Kazakhstan, a pragmatic approach is to start with pilot lines producing sandwich panels and MEP modules with subsequent expansion supported by public procurement and incentive measures (tax incentives, equipment subsidies). Logistics and access to raw materials (thermal insulation materials, metals) also influence unit costs and should be considered in factory location choices.

Energy Efficiency and “Green” Technologies - Reducing Operating Costs and Carbon Footprint. An integrated approach to energy efficiency of industrial buildings includes optimization of form and orientation, a highly efficient building envelope, heat recovery, adaptive façades, distributed generation (solar panels), heat pumps, and intelligent control systems. In projects implemented to ZEB/Passive House and BREEAM/LEED standards, energy consumption reductions of 20-90% have been observed depending on baseline conditions and the depth of interventions [11]. In the industrial sector, technological loads often remain decisive; however, optimizing the envelope and service systems yields significant savings for administrative and auxiliary areas, as well as for heating and ventilation systems.

Figure 3 shows the world ranking of countries by energy efficiency. Design of industrial buildings is not limited to structural calculations and placement of technological equipment; a key factor is optimization of energy consumption and provision of a comfortable microclimate in work areas with minimal operating costs.

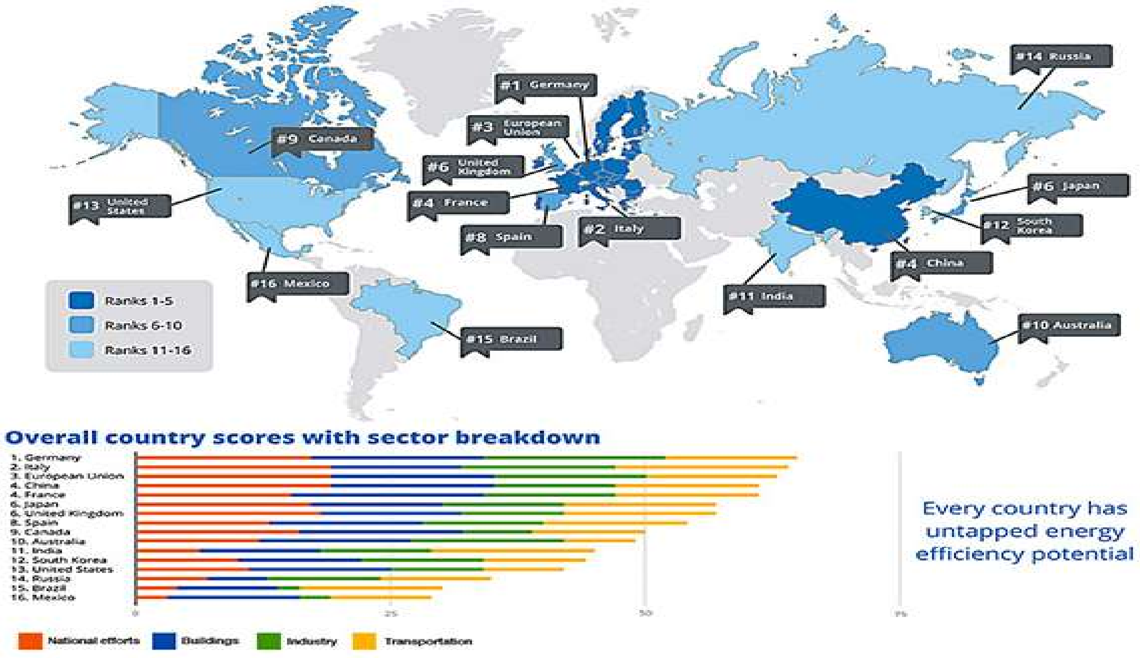

Figure 3 - World ranking of countries by energy efficiency

Modern approaches imply a suite of measures: reinforcing the thermal performance of the envelope considering climatic conditions, designing ventilation systems with heat recovery, implementing automated climate control systems, and selectively deploying renewable energy sources. The economic benefit of these measures manifests in reduced operating costs and, over time, a lower carbon footprint. For objective evaluation of proposed solutions, it is recommended to combine engineering calculations with lifecycle analysis, including assessment of initial costs, operating costs, and end-of-life disposal of materials. Selection of envelope materials and engineering systems should be based not only on initial cost but also on durability, availability of service, and ease of repair.

In Kazakhstan, the continental climate prioritizes enhanced thermal insulation, heat-recovery ventilation systems, and the use of heat pumps, while high solar potential makes rooftop PV systems promising for industrial buildings. It is important to develop national requirements for energy efficiency of industrial envelopes and to incentivize renewable energy deployment via tariffs and tax incentives.

Seismic Resistance - Methods for Reducing Risks to Critical Facilities. In high-seismicity countries (Japan), base isolation, damping devices, and “seismic-resilient” design concepts are widely used to substantially reduce the energy transmitted to structure and equipment. For industrial facilities this is particularly important: destruction or displacement of technological equipment can cause production stoppages and environmental consequences. The use of base isolation and dampers in critical-object projects has demonstrated reductions of seismic accelerations to one-third-one-fifth of initial values and significant savings on recovery after high-intensity events [9].

Ensuring reliability of industrial buildings includes both durability of structural elements and resilience to extreme impacts. In seismic hazard contexts, approaches based on evaluating the behavior of structures and equipment under actual loads are applied, enabling required levels of functionality to be preserved after events. Additionally, design must account for corrosion resistance and local aggressive factors, provide convenient access for maintenance and replacement of units, and implement systems for monitoring the condition of structures and equipment. The combination of appropriate material selection, design solutions and integration of monitoring systems extends maintenance intervals and reduces total life-cycle costs.

Kazakhstan has seismically active regions in the south and southeast. For critical facilities (power plants, refineries, large processing installations), economically justified adoption of modern seismic protection systems is warranted. This requires updating national standards and training designers in performance-based design.

Synergy of Methods and Practical Adaptation Scenarios for Kazakhstan. Adapting international practices to the national context requires consideration of climatic, logistical, economic, and regulatory peculiarities of Kazakhstan. Climatic differences across regions necessitate regional differentiation of thermal requirements for building envelopes and design of ventilation systems accounting for seasonal changes. Logistics realities dictate the need to develop a distributed production model for prefabricated components, establishing regional production facilities that minimize transport costs and supply disruption risks. From a regulatory policy standpoint, it is important to implement digital design requirements in stages, starting with pilot mandates for large public procurements and subsequently developing national BIM model templates. Energy and seismic regulations require adjustment for local specifics: introducing regional threshold values for thermal characteristics of envelopes and mandating performance-based approaches for critical infrastructure.

In terms of economic policy, mechanisms for incentivizing localization of prefabrication should be considered: tax breaks, subsidies for equipment purchase, and concessional loans for module manufacturers. Educational policy must accompany technological changes, ensuring training of specialists in BIM, prefabrication technologies, and management of digital asset operation.

Implementation of the proposed strategy should proceed in sequential steps beginning with a preparatory phase, during which regulatory and organizational foundations are formed. At this stage, a working group is established, national requirements for BIM data exchange are developed, and pilot templates are tested. The next stage involves launching pilot projects to practically verify technological solutions, logistics schemes, and the economic model of prefabrication production; obtained data serve as the basis for refining regulations and methodologies. Thereafter, scaling is pursued, including expansion of mandatory requirements for government procurements, development of a network of regional production facilities, and dissemination of practices within the private sector. The finalization phase is stabilization, during which module solutions are standardized, industry libraries of components are developed, and digital twins are incorporated into routine facility operation. At each stage, monitoring of effectiveness indicators, collection of operational data, and flexible adjustment of adopted measures are critical.

Adoption of new approaches involves organizational, economic and technical risks. Organizational risks include shortage of qualified personnel and resistance to change within the industry; economic risks include substantial initial investments and demand uncertainty; technical risks include logistics shortcomings and absence of a local regulatory base adapted to new approaches. Risk mitigation is possible through combined measures: investment in workforce development and practitioner training, use of public procurement to generate initial demand, provision of financial incentives and subsidies for prefabrication producers, and phased introduction of regulatory requirements accompanied by demonstration of the economic effect via pilot projects. An important instrument is the creation of platforms for experience exchange and attraction of international partners for knowledge transfer and technology adaptation.

Conclusion. International experience (Germany, Japan, the USA, China) demonstrates high effectiveness of integrating BIM, prefabrication, energy-efficient technologies, and seismic protection in industrial building design: reduced construction times, decreased volumes of waste, lower operational energy costs, and increased resilience to natural hazards [1].

Adaptability for Kazakhstan. Kazakhstan is technically and institutionally capable of adapting the listed methods; however, a phased strategy is required that accounts for local climatic, logistical and regulatory features. Key directions include piloting BIM, developing local prefabrication production, tightening energy requirements, and targeted application of seismic protection.

Practical recommendations.

1. Optimal effect is achieved by combining approaches: BIM provides coordination of design decisions and management of prefabrication production; prefabrication accelerates commissioning; energy-efficient solutions reduce operating costs; seismic protection reduces risks for critical assets.
2. Pilot BIM on public industrial projects and large infrastructure procurements; develop national methodologies and provide training [6].
3. Launch mini-plants for production of typical modules (sandwich panels, MEP blocks) with public procurement for initial load and tax incentives [2].
4. Raise energy efficiency requirements for new industrial buildings and promote renewable energy adoption: tenders with energy-efficiency criteria, subsidies for heat pumps and PV systems.

Introduce mandatory seismic vulnerability assessments for highly critical facilities and apply modern protective systems in design.

Future research directions. Quantitative LCA and economic modeling for typical industrial building archetypes in Kazakhstan are required, pilot testing of digital twins for monitoring savings and reliability, and studies on scaling prefabrication and its impact on the local economy.

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ӨНЕРКӘСІПТІК ҒИМАРАТТАРДЫ ЖОБАЛАУ ӘДІСТЕРІН ЗЕРТТЕУ

Аңдатпа. Мақалада Германия, Жапония, АҚШ және Қытайдағы өнеркәсіптік ғимараттарды жобалаудың заманауи әдістеріне салыстырмалы талдау жасалып, анықталған тәжірибелердің Қазақстан жағдайына бейімделу мүмкіндігі бағаланды. Зерттеудің негізгі бағыттарына ғимараттардың ақпараттық үлгілеуі (BIM), модульдік (префабрикаттық) құрылыс, энергия үнемдейтін және төмен көміртекті технологиялар, сондай-ақ сейсмотұрақтылықты арттыру әдістері жатады. Әдістемелік тұрғыдан жұмыс 2018–2025 жылдар аралығындағы ғылыми әдебиеттер мен салалық есептерді жүйелі талдауға, нормативтік құжаттарды зерделеуге және іске асырылған жобаларды салыстырмалы талдауға негізделген. Негізгі назар мерзімдерді қысқарту, қалдықтарды азайту және энергия тұтынуды төмендету сияқты сандық көрсеткіштерге аударылған. Зерттеу нәтижелері көрсеткендей, BIM және модульдік технологияларды біріктіру өндірістік база мен модульдерді стандарттау жағдайында жобалық қателіктерді айтарлықтай азайтып, операциялық тиімділікті арттырады. Энергия тиімді шешімдер (жақсартылған қоршау, жылу қалпына келтіру жүйелері, жаңартылатын энергия көздері) өнеркәсіптік кешендердің энергия шығынын технология мен нысанның бастапқы жағдайына қарай 20–50%-ға дейін төмендетуге мүмкіндік береді. Сейсмоизоляция мен демпферлер жер сілкінісі жиі болатын аймақтарда жабдықтардың жұмыс қабілеттілігін сақтап, ғимаратқа түсетін діріл үдеуін азайтады. Қазақстан үшін бейімдеу стратегиясы кезең-кезеңімен жүзеге асыруды көздейді: мемлекеттік нысандарда BIM жүйесін пилоттық енгізу, жергілікті модульдік құрылыс өндірісін дамыту, өнеркәсіптік ғимараттардың жылу тиімділігіне қойылатын талаптарды күшейту және аса маңызды нысандарда сейсмоқорғаныс жүйелерін мақсатты түрде қолдану. Қорытынды бөлімде нормативтік сүйемелдеу, кадрлық қамтамасыз ету және сандық зерттеулердің болашақ бағыттары бойынша тәжірибелік ұсыныстар берілген.

Тірек сөздер: өнеркәсіптік құрылыс, BIM, модульдік конструкциялар, энергия тиімділік, сейсмотұрақтылық, Қазақстан.

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ИССЛЕДОВАНИЕ МЕТОДОВ ПРОЕКТИРОВАНИЯ ПРОМЫШЛЕННЫХ ЗДАНИЙ

Аннотация. В статье представлен сравнительный анализ современных методов проектирования промышленных зданий в Германии, Японии, США и Китае и оценена применимость выявленных практик для условий Казахстана. Основные направления исследования включают:информационное моделирование зданий (BIM), модульное (префабрикатное) строительство, энергоэффективные и низкоуглеродные технологии, а также методы повышения сейсмостойкости. Методологически работа базируется на систематическом обзоре научной литературы и отраслевых отчётов за 2018–2025 гг., нормативном анализе и сопоставлении реализованных проектов — с акцентом на количественные показатели (сокращение сроков, уменьшение отходов, снижение энергопотребления). Результаты показывают, что интеграция BIM и модульных технологий обеспечивает существенное снижение проектных коллизий и операционные выгоды при условии наличия производственной базы и стандартизации модулей. Энергоэффективные решения (усиленная оболочка, рекуперация, ВИЭ) позволяют сокращать энергозатраты промышленных комплексов на 20–50% в зависимости от технологии и начального состояния объекта. Сейсмоизоляция и демпферы уменьшают передаваемые ускорения и сохраняют работоспособность оборудования в районах с повышенной сейсмичностью. Для Казахстана предложена поэтапная адаптационная стратегия: пилотное внедрение BIM на государственных объектах, развитие локального префаб-производства, введение более жёстких энергостандартов для промышленных оболочек и целевое применение сейсмозащиты для критичных объектов. В заключении содержатся практические рекомендации по нормативному сопровождению, кадровому обеспечению и направлениям дальнейших количественных исследований.

Ключевые слова: промышленное строительство, BIM, модульные конструкции, энергоэффективность, сейсмостойкость, Казахстан.

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