Civil Engineering and Architecture 14(1): 630-641, 2026 http://www.hrpub.org
DOI: 10.13189/cea.2026.140142

Architectural and Design Concept of Prefabricated Housing in the Conditions of Kazakhstan

Inna Ostapenko[1,2], Aray Saibulatova[1,2,*], Alexandr Bryantsev[2,3]

[1]Kazakh Leading Academy of Architecture and Civil Engineering, Almaty, Republic of Kazakhstan
[2]International Educational Corporation, Almaty, Republic of Kazakhstan
[3]Scientific Research Institute "RAS Engineering" LLP, Almaty, Republic of Kazakhstan

Received September 15, 2025; Revised December 9, 2025; Accepted January 12, 2026

Cite This Paper in the Following Citation Styles

***(a):** [1] Inna Ostapenko, Aray Saibulatova, Alexandr Bryantsev , "Architectural and Design Concept of Prefabricated Housing in the Conditions of Kazakhstan," Civil Engineering and Architecture, Vol. 14, No. 1, pp. 630 - 641, 2026. DOI: 10.13189/cea.2026.140142.*

***(b):** Inna Ostapenko, Aray Saibulatova, Alexandr Bryantsev (2026). Architectural and Design Concept of Prefabricated Housing in the Conditions of Kazakhstan. Civil Engineering and Architecture, 14(1), 630 - 641. DOI: 10.13189/cea.2026.140142.*

Abstract The development of the concept of prefabricated low-rise housing adapted to the conditions of Kazakhstan is of particular relevance in the context of specific climatic and geographical features of the region, such as high seismic activity, sharp temperature fluctuations, and the need for rapid deployment of residential facilities in emergency situations. The purpose of this study was to create an architectural and design concept of prefabricated housing with a focus on innovative structural solutions that meet modern requirements for energy efficiency, earthquake resistance and mobility. The study developed and tested three experimental variants of architectural models: block-modular system, containerised assembly, and transformable design. These schemes were chosen due to their prominent degree of industrialisation, the possibility of rapid assembly, and adaptation to the natural and climatic conditions of Kazakhstan. Each model was analysed in detail in terms of speed of assembly, energy efficiency, resistance to seismic loads, and economic feasibility. The findings revealed that the block-modular system demonstrated the best balance between adaptability, energy efficiency, and scalability, making it the most suitable for permanent housing. The containerised system was found to be the most suitable for use in remote areas due to its factory-ready and compact nature, while the transformable design provided high flexibility, making it ideal for temporary and seasonal solutions. The developed architectural model demonstrated high energy efficiency and seismic resistance, as evidenced by heat loss and seismic load calculations, as well as its ability to be used in extreme climatic changes. The seismic resistance of the model was evaluated considering seismic loads of magnitudes 8-9, which confirmed its ability to withstand considerable deformations and stresses. These findings make the proposed concept suitable for mass application in Kazakhstan, both for permanent housing and for emergency deployment of residential facilities.

Keywords Prefabricated Modular Systems, Climate Adaptation, Mobile Residential Structures, Architectural Typology, Design Innovations, Energy-Efficient Solutions, Earthquake Resistance, Design Parameters

1. Introduction

The relevance of the study is conditioned by the urgent need of the Republic of Kazakhstan to create adaptive, prefabricated, and energy-efficient housing capable of promptly responding to the challenges of urbanisation, climatic instability, seismic activity, and social demand in conditions of limited infrastructure, which requires the integration of modular architectural solutions, structural flexibility, and industrial construction technologies.

A series of studies emphasise the efficiency of modular and rapid construction. D.V. Tsygulev & R.B. Sabitov [1] analysed the current state and prospects of modular-block construction in Kazakhstan, paying special attention to its technological advantages for the northern regions of the country. The study emphasised the significance of using industrial methods of housebuilding to accelerate the pace of housing construction and optimise costs, which is of particular relevance in conditions of extreme climatic stresses. A. Dzhumabaev *et al.* [2] considered the problems of introducing robotic solutions in the construction industry of Kazakhstan, focusing on the prospects of automating the processes of construction of modular and prefabricated facilities. The study found that the integration of robotic technologies can markedly increase the productivity of construction work and ensure consistent quality in the construction of housing in challenging climatic conditions. G.A. Karabayev & S.E. Mamedov [3] investigated the phenomenon of architectural triviality in modern residential complexes of Astana city, raising the problems of standardisation and loss of individuality of architectural environment. The researchers emphasised the need to move to more adaptive design models that combine functionality, aesthetics, and consideration of local climatic and cultural features. D.T. Mukayev *et al.* [4] conducted a comprehensive analysis of the current state of housing construction in Kazakhstan, identifying the key barriers to housing affordability for the population. The study highlighted those existing approaches require the introduction of innovative design solutions focused on rapid assembly, modularity, and energy efficiency, especially in the context of growing urbanisation and migration processes. A.S. Yestemessova *et al.* [5] investigated the possibilities of creating energy-efficient lightweight concrete for green building applications in Kazakhstan. The researchers demonstrated that the introduction of new compositions of lightweight concrete can considerably reduce the heat loss of buildings and increase the environmental sustainability of construction projects, which makes this development particularly promising for prefabricated housing in the climatic conditions of Kazakhstan.

L. Chen *et al.* [6] presented a unique experience in the design and accelerated construction of the Leishenshan Modular Hospital in Wuhan in response to the COVID-19 pandemic. The study demonstrated that modular composite buildings are highly efficient in emergency situations, enabling the full cycle of design, fabrication, and erection in the shortest possible time without compromising quality and functionality, which is a valuable benchmark for the design of prefabricated housing. B. Maturana *et al.* [7] analysed the changes in architecture and urban planning in a post-pandemic reality. The researchers noted the growing relevance of virtual and hybrid spaces, the increasing demands for flexibility of the living environment and the sustainability of the urban structure, which reinforce the relevance of the application of modular and adaptive architectural solutions in the new building context. C. Ma *et al.* [8] conducted a systematic review of modification strategies for smart homes for the elderly. The analysis highlighted design principles focused on creating adaptive, safe, and high-tech living environments, confirming the relevance of using modular design to ensure the long-term suitability and sustainability of residential developments. J. Wang *et al.* [9] reviewed the current trends of sustainable urban design in the era of digitalisation. The researchers focused on the need to integrate digital technologies into architectural design to create more adaptive and efficient living spaces, especially relevant to the concept of rapid housing in the context of rapid urbanisation. K. Mouratidis [10] analysed the relationship between urban design features and the level of subjective well-being of the population. The study confirmed that the quality of the architectural environment, its functional richness, and adaptability directly affect the psychological perception of life in the city, which emphasises the value of a human-centred approach in the design of modern housing, including prefabricated housing complexes.

Despite the existing developments, the issue of architectural and design modelling of modular housing with consideration of climatic and social conditions of Kazakhstan continues to be understudied. Most of the available solutions are oriented towards universal standards and are not adapted to the specifics of landscape, ecology, regulatory framework, and historical residential culture. The lack of a comprehensive design approach that combines architectural expressiveness, engineering efficiency, and local parameters prevents the widespread use of these solutions in the construction practice of the country. The purpose of the present study was to develop an architectural and design model of prefabricated low-rise housing for the conditions of Kazakhstan, based on the definition of key factors of climatic, structural, and technological adaptation and the development of design parameters with consideration of the requirements of sustainability and energy efficiency.

2. Materials and Methods

The study was based on the results of design and analytical modelling conducted in September–December 2024. The basis for modelling was the generalised data of modern research in the field of modular and prefabricated construction in Kazakhstan. The studies analysed in this paper provided information on the types of modular systems, the specifics of their application in the climatic conditions of Kazakhstan, the problems of standard design, as well as the requirements for energy efficiency and earthquake resistance of low-rise residential buildings. The analysis of sources helped to systematise current trends in the design of prefabricated residential buildings in Kazakhstan, to identify the specific features of application of modular, mobile, and kinetic architecture in real projects.

The theoretical stage included a review of the concepts of prefabricated, modular, and kinetic architecture, with a focus on their evolution in the early 21st century and adaptation to the requirements of sustainable design. The study analysed the current state of architectural typology of low-rise housing, with systematisation of existing solutions by type of structural schemes, planning modules, and materials of enclosing structures.

To create the architectural and design concept, an experimental model of a low-rise prefabricated house was developed for the extreme natural and climatic conditions of Kazakhstan. Design modelling was performed in several variants, which differ in the type of modular assembly (block-modular, transformable, container) and materials of load-bearing structures (steel, wood, lightweight concrete).

The evaluation of design solutions was based on a multifactor comparative analysis aimed at a comprehensive characterisation of the designed models. The key criteria considered included the degree of adaptability of residential systems to extreme natural and climatic loads (wind, temperature, and seismic), the technological speed of assembly and the level of industrialisation of the construction process, the energy efficiency of buildings under operating conditions, the flexibility of spatial transformation and scalability of modular structures, as well as economic efficiency expressed in the cost of construction and total operating costs in regional conditions of Kazakhstan. Each of these criteria was evaluated on a scale of 1 to 5 points. The evaluation was authors' and reflects subjective expert opinion based on the results of the design analysis and implementation conditions.

As tools for substantiation of design solutions, calculations of thermal characteristics of envelope structures were used, performed based on regulations "Rules of RK 2.03-01-2011" [11], including determination of heat transfer coefficients and compliance with the minimum requirements for thermal resistance for climatic regions IIA and IIB. Additionally, the energy balance of buildings was modelled, accounting for seasonal loads and insolation, which helped to assess the efficiency of the designed solutions in operation.

Earthquake resistance was assessed by applying design parameters following the requirements of "Rules of RK 2.03-30-2017" [12], accounting for the design seismic intensity of 8 and 9 points. This ensured verification of the rigidity and stability of the structural schemes under horizontal loads.

The design and visualisation of the models were conducted using the professional software AutoCAD [13] to construct architectural and structural drawings. The energy efficiency of design solutions was analysed using EnergyPlus [14] calculation modules, which enable dynamic modelling of heat losses, energy consumption for heating and cooling, as well as assessment of the potential for reducing operating costs.

Thus, the applied methodology provided an integrated combination of architectural and compositional search, engineering substantiation, and adaptation of design solutions to the specific requirements of Kazakhstan, which allowed forming a reasonable architectural and design concept of prefabricated low-rise housing.

3. Results

Within the framework of design and analytical modelling, three experimental variants of the architectural model of prefabricated low-rise housing were developed and tested: block-modular system, container assembly, and transformable construction. The choice of these schemes was conditioned by their prominent degree of industrialisation, the possibility of quick assembly at the construction site, as well as potential suitability for operation in conditions of natural and climatic variability typical for the territory of Kazakhstan.

The block-modular system is a set of typical volumes (blocks) assembled on site into a single architectural whole using connecting nodes. This type of construction provides good scalability, flexible configuration of internal spaces, and high speed of assembly. The containerised scheme is based on the use of standard transport dimensions, which makes it particularly attractive for remote or inaccessible regions with limited logistics. Its advantages are compactness, transportability, and full factory availability. At the same time, the transformable modular system is oriented towards temporary or seasonal housing and allows changing the geometry of the object by rotating or sliding elements, which makes it suitable for conditions with sharp temperature fluctuations and variable demand for living space.

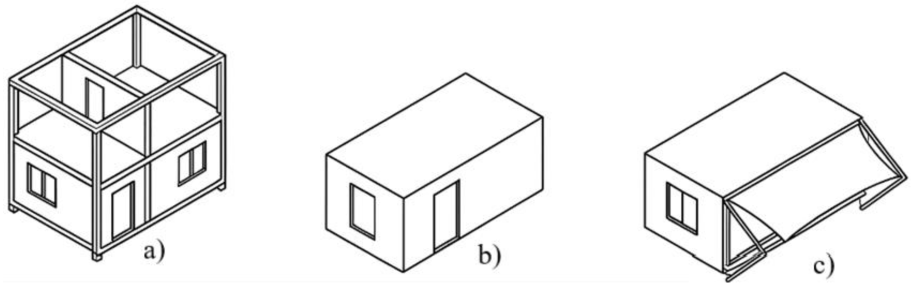
The choice of these models was based on the need to compare design solutions with different structural structures, degree of adaptability, and assembly logic. A visual representation of the structural structure of the above systems is presented in Figure 1.

As Figure 1 shows, each of the presented modular schemes demonstrates individual features of spatial and structural organisation. The block-modular system (a) forms a stable two-level volume with the possibility of vertical and horizontal combination of blocks, which provides good scalability and variety of planning solutions. The containerised variant (b) is characterised by maximum factory availability and compactness, focusing on standardised logistics. The transformable scheme (c) is characterised by its dynamic design - the presence of retractable and tilting elements, enabling flexible adaptation of the shape and volume of the living space depending on the season, user scenarios, or deployment site. The types presented serve as a baseline for a more in-depth evaluation of the design solutions in the following stages of the analysis.

A comparative table of basic parameters, such as overall mass, type of assembly, assembly cycle time, and factory availability, was compiled to provide a preliminary assessment of the applicability of each modification. These characteristics are presented in Table 1 and serve as a starting point for the subsequent multifactor analysis of the design solutions.

As Table 1 shows, the containerised system demonstrates the greatest indicators of applicability in the conditions of Kazakhstan, characterised by the minimum overall weight, maximum degree of factory availability, and the shortest terms of the assembly cycle. Therewith, the transformable system surpasses others in terms of flexibility of configuration and potential for functional adaptation, which makes it particularly promising for temporary and seasonal scenarios of use. The block-modular scheme, despite its longer assembly cycle, provides the greatest potential for scalability and customisation of architectural solutions, which may be critical in the design of permanent housing in developing areas.

To comprehensively evaluate the proposed design solutions, a multifactor comparative analysis of the three modular systems was conducted based on five key criteria identified in the methodological part of the study: adaptability to climatic conditions, energy efficiency in operation, speed and manufacturability of assembly, flexibility of transformation and scalability, and economic efficiency expressed through construction and operating costs. For each criterion, an expert scale from 1 to 5 points was applied, where 5 corresponded to the maximum positive evaluation. The final scores are presented in graphical form to visualise the strengths and weaknesses of each modification (Figure 2).



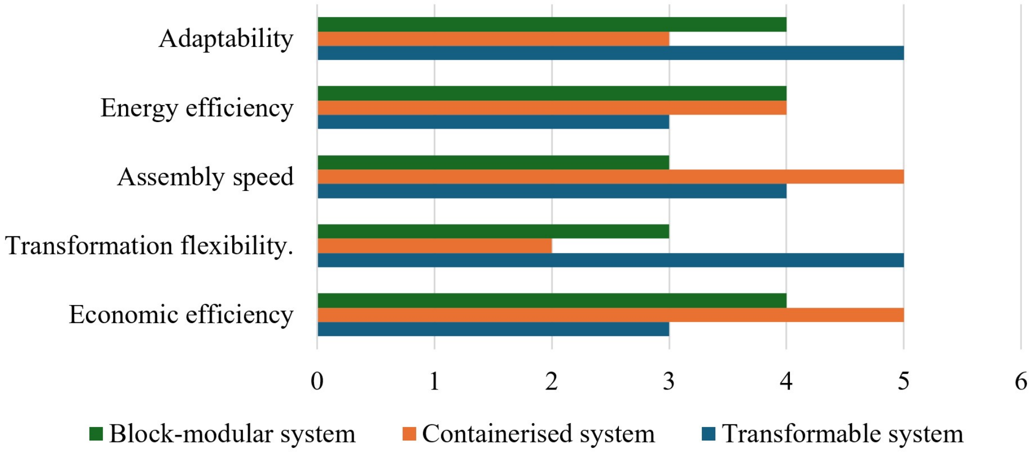
Source: compiled by the authors

Figure 1. Comparative diagram of three modular systems: (a) block-modular, (b) containerised, (c) transformable

Table 1. Comparative characterisation of basic parameters of modular systems

	Parameters	Block-modular system	Containerised system	Transformable system
1	Overall weight (t)	5-8	2.5-4	3-5
2	Assembly type	Combinable on site	Fully prefabricated units	Sliding/tilting mechanics
3	Assembly cycle time	7-10 days	1-3 days	3-6 days
4	Degree of factory availability	Medium	Maximum	High

Source: compiled by the authors based on data from D.V. Tsygulev, & R.B. Sabitov [1], A. Dzhumabaev *et al.* [2]



Source: compiled by the authors

Figure 2. Diagram of the final evaluation of the effectiveness of project solutions (according to five criteria)

Figure 2 presents a radar diagram illustrating the integrated performance distribution of the three low-rise, prefabricated housing design models according to five key criteria: climate adaptability, energy efficiency, speed and technology of assembly, flexibility of transformation and scalability, and cost-effectiveness. Visual comparison allows clearly distinguishing the features of each system: the containerised model demonstrates a pronounced advantage in assembly speed and cost, the transformable model – in adaptability and flexibility of architectural solution, while the block-modular scheme is characterised by the most balanced profile of indicators, with no evident failures in certain criteria.

Based on the conducted multifactor analysis, the block-modular system with elements of transformation of internal space was recognised as optimal for the conditions of Kazakhstan. This model provides the best balance between adaptability to climatic loads, assembly technology, energy efficiency, and scalability of residential units.

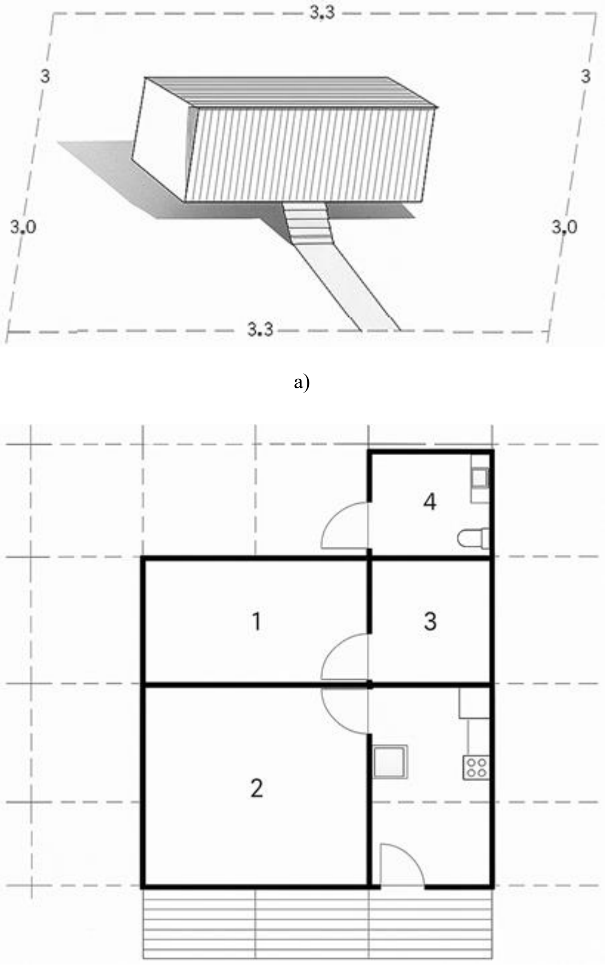
The structure of the model is based on the principles of free layout of modules, connected to each other according to the scheme "volume in volume", which provides flexibility in shaping and allows adapting planning solutions for different functional scenarios. The layout of the blocks is organised on an orthogonal grid with a module spacing of 3.6×3.6 m, which corresponds to standard transport dimensions and simplifies assembly logistics.

The basic volumetric and spatial organisation provides a modular connection of residential, service and communication zones. The ground floor consists of a central shared space (living room with kitchen area) flanked by two sleeping units with bathrooms. If necessary, the model allows for both horizontal expansion by adding more residential units and vertical expansion of the second level.

The functional layout provides clear zoning of private and public spaces, as well as insolation optimisation due to the orientation of the core rooms to the south and east. The architectural solutions utilise lightweight prefabricated façade panels with insulation, which allows the project to be quickly adapted to the concrete climatic requirements of the region.

A visual representation of the site masterplan and ground floor layout is presented in Figure 3.

Figure 3 presents the architectural and planning scheme of the ground floor of the prototype of a low-rise prefabricated dwelling house made according to the principle of the block-modular system with a modular grid of 3×9 metres. The plan clearly demonstrates the structure of spatial zoning based on the connection of four standard volume-spatial modules, each of which represents a complete functional element. Module 1 includes an entrance group and a sanitary service area with a vestibule, a bathroom, and a technical alcove. Module 2 is used for the communal part – kitchen and dining room - organised in a single spatial volume with orientation to the east, which provides morning insolation. Modules 3 and 4 perform the function of dwelling spaces – bedrooms, each with a separate exit to the outdoor terrace, as well as the possibility of installing partitions for individual division of space. The plan emphasises the strict modularity and adaptive structure, providing flexibility in scaling the building both horizontally (by docking more modules) and vertically (first floor extension is allowed). The arrangement of window and door openings is synchronised with the pitch of the load-bearing panels, which allows for standardisation of the façade elements and facilitates re-production. All load-bearing structures are oriented along the axes of the modular grid, which simplifies the calculation and expedites the assembly process at the construction site. Thus, the presented plan demonstrates the key principles of modular architecture: typification, repeatability, manufacturability, and functional completeness of each element, which makes this model suitable for mass industrial construction in a variety of climatic regions of Kazakhstan.



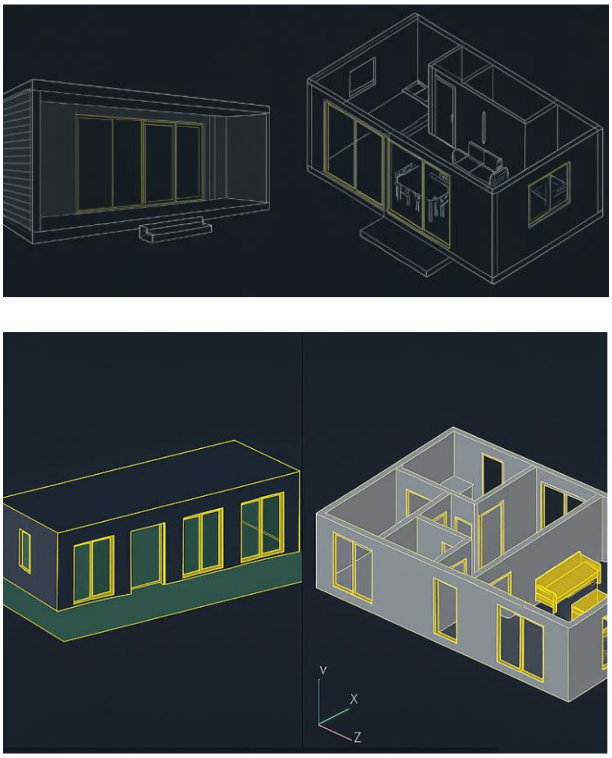
a)

b)

Source: compiled by the authors based on AutoCAD

Figure 3. (a) Masterplan and (b) ground floor plan of the selected architectural model

The three-dimensional visualisation of the facade solution and the interior space of the model, presented in Figure 4, demonstrates laconic architectural plasticity, the use of large, glazed openings to maximise natural insolation, and the creation of a functionally rich but compact internal environment.



Source: compiled by the authors based on AutoCAD

Figure 4. 3D visualisation of facade and interior space

Figure 4 presents a three-dimensional visualisation of the facade and interior architectural solution of the optimal model of a prefabricated low-rise residential building made in AutoCAD using volumetric modelling tools. The model demonstrates the strictness of geometry and rational compositional organisation, typical for block-modular design, where each architectural element is subordinated to the logic of seriality and production compatibility.

The facade solution is based on the principles of translucency and modular repeatability: large-format glazed openings evenly distributed around the perimeter provide maximum natural insolation of rooms, especially when the primary facade plane is oriented to the southeast. The architectural plasticity is kept in a minimalist aesthetics, without excessive decorative saturation, which corresponds to the objectives of typical industrial construction and reduces operating costs.

The interior space of the model, partially revealed in an isometric section, emphasises the functional clarity of zoning. The living modules are separated from the sanitary and communication core, which contributes to both energy-efficient heating and soundproofing. The placement of furniture and engineering elements within each module illustrates the possibility of factory fit-out and assembly with minimal wet processes on site.

The presented visualisation allows evaluating not only formal qualities of the design solution, but also its applied feasibility in the context of scalable housing construction in climatic and technogenic conditions of Kazakhstan.

To assess the thermal performance of the selected architectural model, the key indicators of heat transfer resistance for structural elements such as external walls, roof, and floor slab were calculated. The calculations were made with consideration of the specific climatic features of Kazakhstan and current regulations, such as “Rules of RK 2.03-01-2011”. Table 2 presents a comparative analysis of calculated and normative values of heat transfer resistance for these structural elements.

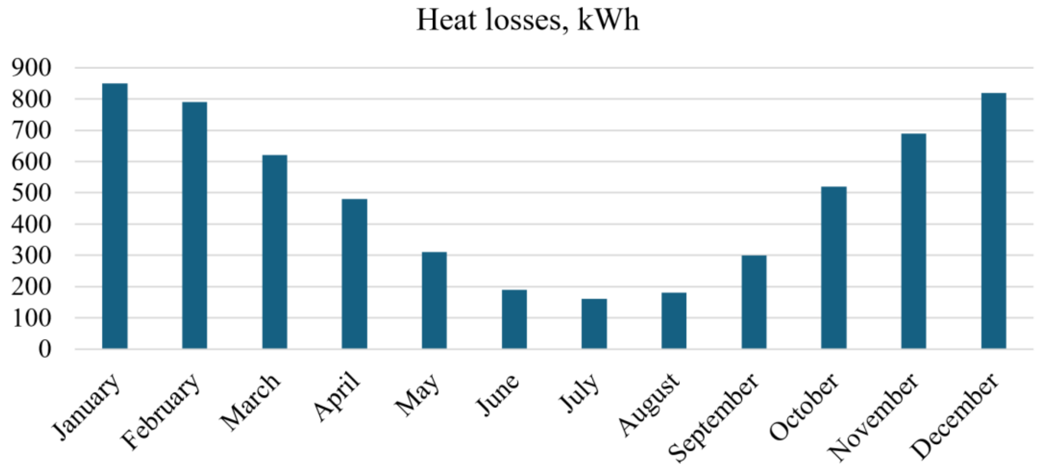
As Table 2 shows, the calculated values of heat transfer resistance for the roof and slabs are in full compliance with the “Rules of RK 2.03-01-2011”, which confirms that the designed building meets the current energy efficiency requirements for the climatic conditions of Kazakhstan. These structural elements provide reliable thermal insulation, which minimises heat losses in the cold season and increases the overall energy balance of the building. For external walls, the calculated value of heat transfer resistance slightly exceeds the normative value, which is a significant factor for improving the thermal insulation characteristics of the structure. Increasing the heat transfer resistance of external walls contributes to a significant reduction of heat losses in winter, which makes the building more energy efficient. This approach is especially relevant for regions with harsh winters, where efficient thermal insulation helps to reduce energy consumption for heating and improve the comfort of living in houses.

To estimate the heat loss of the building during the year, heat balance modelling was performed, the results of which are presented in Figure 5.

Table 2. Thermal performance of structures (comparison of design and normative values)

Structural element	**Design heat transfer resistance, m^2×°C/W**	**Normative value according to “Rules of RK 2.03-01-2011”, m^2×°C/W**
Exterior wall	3.25	2.8
Roofing	4.1	4.0

Source: compiled by the authors



Source: compiled by the authors based on EnergyPlus

Figure 5. Heat loss graph by season (winter/summer)

Figure 5 presents the projected heat losses of the building by month in winter and summer. The largest values of heat losses are observed in the cold months, from September to March, which is related to the need for supplementary heating to maintain a comfortable indoor temperature. In these months, heat losses reach their maximum values, amounting to 850 kWh, which confirms the high load on the heating system at insufficient external temperature. During the warm period (from May to August), heat losses are markedly reduced and amount to only 190 kWh, which reflects the high thermal insulation characteristics of the building. These data confirm the effectiveness of design solutions aimed at improving energy efficiency, as well as at optimising energy use in the diverse climatic conditions of Kazakhstan. The predicted reduction in heat loss in the summer months is caused by the possibility of minimising the heating demand due to high-quality thermal insulation, as well as the effective use of natural insolation and ventilation. Thus, Figure 5 demonstrates that the building has prominent energy efficiency throughout the year, which reduces energy consumption and contributes to savings in operating costs, especially in winter.

In addition to energy balance and thermal performance, the comprehensive evaluation of the building also included an assessment of seismic stability as an integral component of overall resilience. Calculations were performed for seismic loads of 8–9 on the MSK-64 scale in accordance with the “Rules of RK 2.03-30-2017,” which reflect the conditions of Kazakhstan’s seismically active zones. The results confirmed that the main structural elements – walls, roof, and floor slabs – maintain integrity under horizontal dynamic loads, while higher stress concentrations were observed only at the modular connection joints (3.4 mm displacement, 0.55 MPa stress). When interpreted together with the results of the thermal and energy modelling, these findings indicate that the proposed prefabricated design demonstrates balanced performance: minimising heat loss in extreme temperatures while ensuring stability and safety under seismic impact. This integrated outcome highlights the model’s ability to maintain operational comfort, structural durability, and energy efficiency under the combined influence of climatic and geological factors characteristic of Kazakhstan.

The modelling results presented in Table 3 show the maximum displacements and stresses in the structural elements under 8- and 9-magnitude loads and identify potentially vulnerable areas of the building.

As indicated in Table 3, the maximum displacement was observed at the corner joints between modules (3.4 mm), which are identified as the most vulnerable points of the structure. This localisation of seismic forces demonstrates that the modular connection areas are subject to the highest stress concentrations, reaching 0.55 MPa, and therefore require particular reinforcement to prevent deformation or potential structural damage during high-intensity earthquakes. In contrast, the other structural elements – external walls, roof, and floor slabs – exhibited significantly lower displacement and stress indicators, confirming their stability and low seismic risk. In general, the obtained data show that the building’s thermal insulation and energy-saving characteristics are effectively supported by its mechanical robustness and seismic stability. The integrated evaluation confirms that the designed prefabricated model ensures reliable performance under combined climatic and seismic impacts, reducing heat loss in extreme weather while maintaining the strength and durability of the structure. Thus, the proposed architectural solution demonstrates a high level of overall resilience and adaptability to the complex natural and geological conditions of Kazakhstan.

To evaluate the energy efficiency of the proposed architectural model, EnergyPlus software was used to perform a detailed calculation of the energy performance of the building, including energy consumption for heating, cooling, and lighting. Modelling was performed considering seasonal changes, temperature fluctuations, and insolation typical for the climate of Kazakhstan, as well as internal load associated with the intensity of use of the premises.

Estimated energy consumption results were provided for each of the building zones, which helped to identify not only the total amount of energy consumed, but also the level of energy consumption by individual consumers, such as heating, ventilation, lighting, and air conditioning systems. Table 4 presents the monthly energy consumption data obtained from the modelling for each of the building zones.

Calculations suggest that the greatest energy consumption occurs during the winter months (October-March), when active operation of the heating system is required to maintain a comfortable indoor temperature. At this time, outdoor temperatures drop significantly, which requires increased energy consumption to maintain the indoor microclimate. These months are characterised by maximum heat losses, which causes intensive use of the heating system, especially at night, when the outside temperature is much lower. Summer months (May–August) are characterised by a decrease in energy consumption for heating due to hotter outdoor temperatures. However, during this period, there is an increase in energy consumption for cooling due to hotter temperatures and the need to maintain a comfortable indoor temperature. During the summer months, the load on air conditioning and ventilation systems increases, resulting in greater overall energy consumption despite no heating demand. This seasonal peak in cooling energy consumption is particularly noticeable in the hot climate of Kazakhstan, where summer temperatures can reach high values. Thus, the building model shows a classic seasonal energy consumption pattern where heating dominates during the cold period and cooling during the warm period, which requires special attention to energy efficiency and optimisation of heating and cooling systems. Figure 6 is an energy profile of the building presenting the seasonal energy consumption dynamics.

Table 3. Results of seismic modelling: displacements, stresses, risk zones

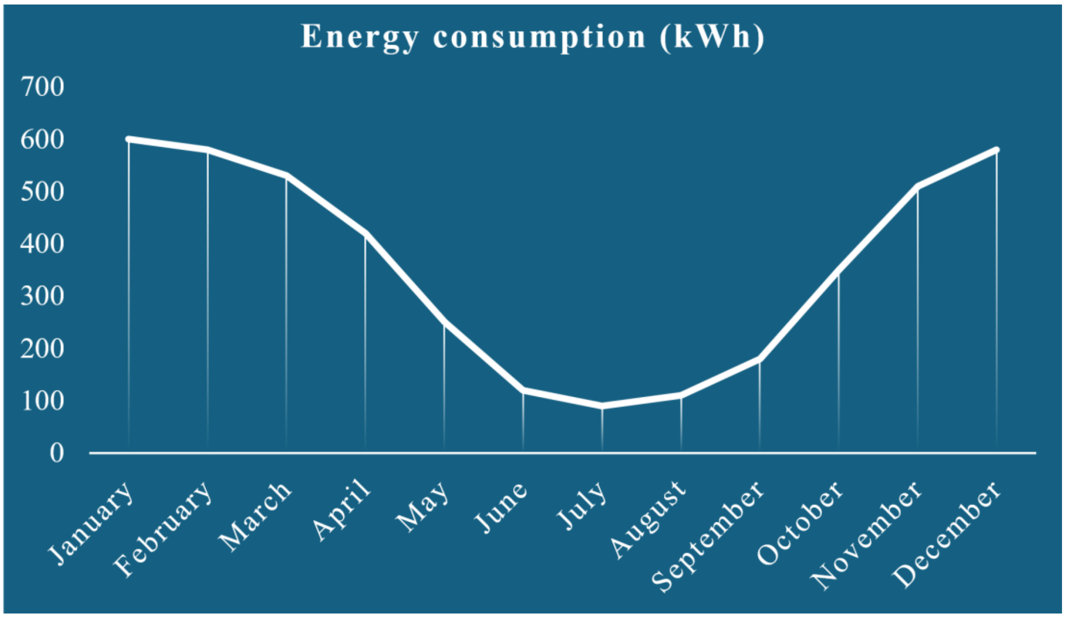
Construction element	Displacement, mm	Stresses, MPa	Risk zones
Exterior wall	1.5	0.35	Low risk
Roof	0.9	0.25	Low risk
Floor slab	1.2	0.28	Low risk
Connection between modules (corner area)	3.4	0.55	High risk

Source: compiled by the authors

Table 4. Monthly energy consumption by zone (in kWh)

Month	Zone 1 (Heating)	Zone 2 (Lighting)	Zone 3 (Cooling)
January	600	120	50
February	580	130	60
March	530	140	90
April	420	150	110
May	250	160	160
June	120	170	180
July	90	180	200
August	110	190	210
September	180	180	180
October	350	160	130
November	510	140	90
December	580	130	60

Source: compiled by the authors



Source: compiled by the authors based on EnergyPlus

Figure 6. Energy profile of the building

Figure 6 allows visualising how energy consumption varies depending on the time of year. During the winter period (October to March), energy consumption increases significantly, reaching peak values of about 600-580 kWh per month. This data confirms that the principal driver of energy consumption in winter is the heating system, which operates at high load to maintain a comfortable temperature in low outdoor temperatures. During the summer months (May to August), the energy consumption decreases due to the reduced heating demand, but there is an increase in cooling energy consumption. This leads to an increase in energy consumption up to 120-180 kWh per month, depending on the outside temperature and insolation level. Therewith, the reduction in heating demand is most noticeable, which contributes to energy savings. These results highlight that by using highly efficient heating and cooling systems and optimised thermal insulation, the building shows considerable savings compared to conventional building solutions. The data in the graph confirms the high energy efficiency of the proposed model, which contributes to the reduction of heating and cooling operating costs. The application of modern technologies, such as energy-efficient heating, cooling, and insulation systems, as well as careful consideration of the thermal performance of the structure, ensures minimal energy consumption, which makes the project more resilient to changes in the energy market and reduces the environmental impact.

The developed architectural model has significant potential for large-scale implementation in the conditions of Kazakhstan, both for the construction of permanent housing and for the creation of temporary or emergency residential facilities. The modular system, with its high adaptability and energy efficiency, enables the rapid and high-quality construction of buildings that can meet various housing needs, both permanent and temporary.

4. Discussion

Within the framework of the conducted study, the architectural concept of prefabricated low-rise housing adapted to the specific conditions of Kazakhstan was developed and tested. The study considered three experimental variants of modular systems: block-modular, containerised, and transformable. The choice of these systems was conditioned by their prominent degree of industrialisation, the possibility of quick assembly at the construction site, and potential suitability for operation in conditions of variable climate and seismic activity typical for Kazakhstan. J. Knippers *et al.* [15] examined an integrated approach to computational design and construction, emphasising the rethinking of architecture through digital technologies. The study highlighted that digitalisation in architectural design enables more adaptive and optimised designs. This approach can be useful in the given context, where digital tools such as Building Information Modelling (BIM) help to improve the design and expedite the construction process, which is relevant for the development of prefabricated housing in Kazakhstan.

S. Gamble [16], S. Hamideh *et al.* [17] considered building mobility as a reconstruction tool for rapidly changing urban environments. This study emphasised the significance of building mobility, which is of direct relevance to the conducted project, as the proposed model of prefabricated housing with modular structures has the flexibility required for rapid deployment in emergency situations or changing conditions.

E.B. Equere *et al.* [18] examined the impact of rapid population growth on public housing schemes and their influence on urban resilience. This study focused on the need to adapt housing patterns to the rapid urbanisation process and changes in demographic structure, which highlighted the value of design solutions that focus on the needs of Kazakhstan's growing population. A. Verzoni & M. Rais-Rohani [19] analysed origami-inspired folding shelter concepts for temporary shelters. This study was related to the research design because it emphasised the creation of temporary shelter solutions that can be quickly installed and adapted to changing conditions, which is particularly relevant for emergency situations in remote and inaccessible regions of Kazakhstan.

R. Chippagiri *et al.* [20] used a cradle-to-site approach in their life cycle assessment study of a sustainable prefabricated housing system. This confirmed the value of using sustainable building solutions that can be adapted to diverse climatic conditions and terrain types, which is also applicable to this architectural concept for Kazakhstan. I. Katz [21] considered mobile architecture as a means of expansion and decolonisation, which is relevant to the design of housing that should be flexible and adaptable in different cultural and geographical contexts. The modular architecture proposed in this project has such characteristics that allow using it for both permanent and temporary housing in different regions of Kazakhstan.

In their review of the use of the Internet of Things (IoT) for energy-efficient buildings and cities, K.M. Al-Obaidi *et al.* [22] emphasised the significance of implementing smart technologies in construction to improve energy efficiency. This confirms the value of integrating modern technologies into the architecture of prefabricated housing to achieve high energy efficiency, which is particularly relevant for Kazakhstan, where energy consumption for heating is significant in winter. J.X. Zhou *et al.* [23], Askar *et al.* [24] investigated the integration of IoT and BIM technologies for the customisation of assembly services on construction sites. This study confirmed that the use of these technologies can extensively expedite the construction process, improve accuracy, and reduce costs, which is also an essential component of the design of prefabricated housing in Kazakhstan.

H.N. Rafsanjani & A.H. Nabizadeh [25] and J. Crippa & C.M.L. Ugaya [26] explored digital architecture, engineering, and construction (AEC) through virtual design, construction (VDC), and digital twins, highlighting their roles in enhancing design accuracy and reducing construction time. In the present study, similar digital tools such as BIM and IoT, are proposed to optimise prefabricated housing design in Kazakhstan, improving efficiency and adaptability to climatic conditions. J.M. Rožanec et al. [27] examined the integration of artificial intelligence (AI) in AEC with a human-centred approach, showing its potential to enhance energy efficiency and earthquake resistance—objectives aligned with this research. M.-H. Shin et al. [28] confirmed the effectiveness of BIM in achieving precision and sustainability in infrastructure projects, while K. Lawal & H.N. Rafsanjani [29] emphasised the importance of IoT for energy management. Collectively, these studies support the use of digital technologies to improve the quality, sustainability, and resilience of prefabricated housing in Kazakhstan.

M. Noghabaei *et al.* [30] analysed trends in the application of virtual and augmented reality in architecture, engineering, and construction, highlighting the relevance of digital technologies to create more interactive and adaptive architectural solutions. This study also opens opportunities for the use of virtual reality in the design and modelling of prefabricated residential projects, which can increase the flexibility and accuracy of design solutions.

J. Ren *et al.* [31], D. Indrawanto [32] reviewed research to improve urban flood early warning and the implementation of new modular relocation systems. This study emphasised the value of modular solutions for emergency housing in natural disasters, which coincides with the goals of the present study to create flexible and sustainable architectural solutions for emergency situations. T. Moore & A. Doyon [33], R.J. Sanchaniya *et al.* [34] considered the transition to sustainable housing and the prospects for low carbon housing solutions. The researchers emphasised the significance of environmental sustainability and energy efficiency, which is a major aspect of developing a proposed architectural model for Kazakhstan, considering the current environmental and sustainability requirements.

Thus, the findings of the present study are in line with current scientific approaches to the design and construction of prefabricated residential projects, especially in the context of the use of innovative technologies such as modular architecture, digital design, and adaptive structures. The application of these techniques can markedly improve energy efficiency, shorten construction time, and increase the resilience of buildings to extreme climatic conditions. The results also confirmed the need to integrate digital solutions such as BIM and IoT to improve the quality and flexibility of design solutions, which could be the basis for mass application of this concept in the Kazakhstan context, both for permanent and temporary housing.

5. Conclusions

The conducted study confirmed the high efficiency of the proposed architectural model of prefabricated low-rise housing for the conditions of Kazakhstan, with consideration of the climatic and seismic features of the region. Based on design-analytical modelling, three experimental variants were developed: block-modular system, containerised assembly, and transformable construction, which allowed identifying the strengths and weaknesses of each model.

The research process comprehensively evaluated these models against a series of key criteria, such as climate adaptability, energy efficiency, speed, and manufacturability of assembly, flexibility of transformation, and cost-effectiveness. The results of the multivariate analysis showed that the block-modular system with space transformation elements is the most suitable for permanent housing as it provides the best balance between adaptability, manufacturability, and energy efficiency. The containerised model, on the other hand, demonstrated a prominent degree of factory readiness and short assembly times, making it ideal for temporary facilities such as emergency situations or temporary camps. The transformable model, although slightly less energy efficient, is uniquely flexible, enabling the adaptation of the interior space to the season or specific user needs.

The developed experimental model accounts for high wind loads, temperature stress, and seismic activity, making it suitable for operation in seismically active areas of Kazakhstan. It also provides high energy efficiency, which was confirmed by the results of thermal modelling using EnergyPlus and predicted heat losses. The seismic resistance of the model was assessed for seismic loads of magnitudes 8-9, confirming its ability to withstand significant deformations and stresses, especially in the corner areas of the connections between modules. This makes the model suitable for construction in seismically active regions of Kazakhstan, ensuring the safety and durability of the structure. Thus, the proposed concept of prefabricated housing can be successfully applied both to the design of permanent residential facilities and to emergency or temporary constructions in the conditions of variable climate and seismic activity of Kazakhstan.

The findings of the present study have crucial applied value for the development of effective and adaptive solutions in construction, especially under conditions of limited time and resources. To further improve the model, it is recommended to expand the experimental base to include data from different regions and to investigate more complex interactions between parameters to increase the versatility and predictive power of the model in the future.

REFERENCES

[1] Tsygulev D.V., Sabitov R.B., "Current state and analysis of the development of modular block construction," Bulletin of the North Kazakhstan University named after M. Kozybayev, vol. 1, no. 46, pp. 204–210, 2021. Retrieved from https://vestnik.ku.edu.kz/jour/article/view/278.

[2] Dzhumabaev A., Olzhabay H., Almaz O., "Problems of implementation and implementation of construction with the use of robotics in the construction industry of Kazakhstan," Problems of Engineering and Professional Education, vol. 70, no. 3, pp. 43–53, 2024. DOI: 10.32523/2220-685X-2023-70-3-43-53.

[3] Karabayev G.A., Mamedov S.E., "The risks of triviality in the architecture of modern residential complexes (in the example of Astana)," Bulletin of L.N. Gumilyov Eurasian National University. Technical Science and Technology Series, vol. 149, no. 4, pp. 351–362, 2024. DOI: 10.32523/2616-7263-2024-149-4-351-362.

[4] Mukayev D.T., Shalbolova U.Zh., Salykov A.M., "Current state of housing construction and housing affordability in Kazakhstan," Bulletin of the Turan University, vol. 1, pp. 279–296, 2023. Retrieved from https://vestnik.turan-edu.kz/jour/article/view/3242.

[5] Yestemessova A.S., Altayeva Z.N., Yesselbayeva A.G., "Energy-efficient lightweight concrete for green building," Bulletin of Kazakh Leading Academy of Architecture and Construction, vol. 2, no. 88, pp. 153–161, 2023. DOI: 10.51488/1680-080X/2023.2-17.

[6] Chen L., Yuan R., Ji X., Lu X., Xiao J., Tao J., Kang X., Li X., He Z., Quan S., Jiang L., "Modular composite building in urgent emergency engineering projects: A case study of accelerated design and construction of Wuhan Thunder God Mountain/Leishenshan hospital to COVID-19 pandemic," Automation in Construction, vol. 124, article number 103555, 2021. DOI: 10.1016/j.autcon.2021.103555.

[7] Maturana B., Salama A.M., McInneny A., "Architecture, urbanism and health in a post-pandemic virtual world," International Journal of Architectural Research Archnet, vol. 15, no. 1, pp. 1–9, 2021. DOI: 10.1108/arch-02-2021-0024.

[8] Ma C., Guerra-Santin O., Mohammadi M., "Smart home modification design strategies for ageing in place: A systematic review," Journal of Housing and the Built Environment, vol. 37, no. 2, pp. 625–651, 2021. DOI: 10.1007/s10901-021-09888-z.

[9] Wang J., Cao S., Yu C.W., "Development trend and challenges of sustainable urban design in the digital age," Indoor and Built Environment, vol. 30, no. 1, pp. 3–6, 2020. DOI: 10.1177/1420326x20976058.

[10] Mouratidis K., "Urban planning and quality of life: A review of pathways linking the built environment to subjective well-being," Cities, vol. 115, article number 103229, 2021. DOI: 10.1016/j.cities.2021.103229.

[11] Rules of RK 2.03-01-2011, "Buildings on undermined territories and soil subsidence," 2011. Retrieved from https://online.zakon.kz/Document/?doc_id=32511439&pos=1;-16#pos=1;-16.

[12] Rules of RK 2.03-30-2017, "Construction in seismic zones," 2017. Retrieved from https://online.zakon.kz/Document/?doc_id=36128461.

[13] AutoCAD, "Overview," Autodesk. Retrieved from https://www.autodesk.com/products/autocad/overview.

[14] EnergyPlus, "About the software," Retrieved from https://energyplus.net/.

[15] Knippers J., Kropp C., Menges A., Sawodny O., Weiskopf D., "Integrative computational design and construction: Rethinking architecture digitally," Civil Engineering Design, vol. 3, no. 4, pp. 123–135, 2021. DOI: 10.1002/cend.202100027.

[16] Gamble S., "House relocation: A redevelopment tool for rapidly changing urban environments," Cities, vol. 154, article number 105233, 2024. DOI: 10.1016/j.cities.2024.105233.

[17] Hamideh S., Peacock W.G., Van Zandt S., "Housing type matters for pace of recovery: Evidence from Hurricane Ike," International Journal of Disaster Risk Reduction, vol. 57, article number 102149, 2021. DOI: 10.1016/j.ijdrr.2021.102149.

[18] Equere E.B., Ibem E.O., Alagbe O.A., "Impact of rapid population growth on public housing schemes and the influence on city resilience," IOP Conference Series Earth and Environmental Science, vol. 665, no. 1, article number 012006, 2021. DOI: 10.1088/1755-1315/665/1/012006.

[19] Verzoni A., Rais-Rohani M., "Transition analysis of flat-foldable origami-inspired deployable shelter concepts," Engineering Structures, vol. 273, article number 115074, 2022. DOI: 10.1016/j.engstruct.2022.115074.

[20] Chippagiri R., Biswal D., Mandavgane S., Bras A., Ralegaonkar R., "Life cycle assessment of a sustainable prefabricated housing system: A cradle-to-site approach based on a small-scale experimental model," Buildings, vol. 13, no. 4, article number 964, 2023. DOI: 10.3390/buildings13040964.

[21] Katz I., "Mobile colonial architecture: Facilitating settler colonialism’s expansions, expulsions, resistance, and decolonisation," Mobilities, vol. 17, no. 2, pp. 213–237, 2022. DOI: 10.1080/17450101.2021.2000838.

[22] Al-Obaidi K.M., Hossain M., Alduais N.A.M., Al-Duais H.S., Omrany H., Ghaffarianhoseini A., "A review of using IoT for energy efficient buildings and cities: A built environment perspective," Energies, vol. 15, no. 16, article number 5991, 2022. DOI: 10.3390/en15165991.

[23] Zhou J.X., Shen G.Q., Yoon S.H., Jin X., "Customization of on-site assembly services by integrating the internet of things and BIM technologies in modular integrated construction," Automation in Construction, vol. 126, article number 103663, 2021. DOI: 10.1016/j.autcon.2021.103663.

[24] Askar R., Bragança L., Gervásio H., "Adaptability of buildings: A critical review on the concept evolution," Applied Sciences, vol. 11, no. 10, article number 4483, 2021. DOI: 10.3390/app11104483.

[25] Rafsanjani H.N., Nabizadeh A.H., "Towards digital architecture, engineering, and construction (AEC) industry through virtual design and construction (VDC) and digital twin," Energy and Built Environment, vol. 4, no. 2, pp. 169–178, 2021. DOI: 10.1016/j.enbenv.2021.10.004.

[26] Crippa J., Ugaya C.M.L., "Optimization and simulation in infrastructure projects using BIM," PARC Research in Architecture and Construction, vol. 15, article number eo24010, 2024. DOI: 10.20396/parc.v15i00.8674190.

[27] Rožanec J.M., Novalija I., Zajec P., Kenda K., Ghinani H.T., Suh S., Veliou E., Papamartzivanos D., Giannetsos T., Menesidou S.A., Alonso R., Cauli N., Meloni A., Recupero D.R., Kyriazis D., Sofianidis G., Theodoropoulos S., Fortuna B., Mladenić D., Soldatos J., "Human-centric artificial intelligence architecture for Industry 5.0 applications," International Journal of Production Research, vol. 61, no. 20, pp. 6847–6872, 2022. DOI: 10.1080/00207543.2022.2138611.

[28] Shin M.-H., Jung J.-H., Kim H.-Y., "Quantitative and qualitative analysis of applying building information modeling (BIM) for infrastructure design process," Buildings, vol. 12, no. 9, article number 1476, 2022. DOI: 10.3390/buildings12091476.

[29] Lawal K., Rafsanjani H.N., "Trends, benefits, risks, and challenges of IoT implementation in residential and commercial buildings," Energy and Built Environment, vol. 3, no. 3, pp. 251–266, 2021. DOI: 10.1016/j.enbenv.2021.01.009.

[30] Noghabaei M., Heydarian A., Balali V., Han K., "Trend analysis on adoption of virtual and augmented reality in the architecture, engineering, and construction industry," Data, vol. 5, no. 1, article number 26, 2020. DOI: 10.3390/data5010026.

[31] Ren J., Zhang S., Li W., Meng L., Yu H., Guo Z., "Research on the urban flood disaster refined early warning and the new modular resettlement systems," in ICBDDM ‘24: Proceedings of the 2024 International Conference on Big Data and Digital Management, Association for Computing Machinery, New York, 2024, pp. 501–509. DOI: 10.1145/3696500.3696584.

[32] Indrawanto D., "Integration of sustainable architecture principles in vertical housing design in high-density urban areas," Journal of Academic Science, vol. 2, no. 2, pp. 461–469, 2025. Retrieved from https://thejoas.com/index.php/thejoas/article/view/244.

[33] Moore T., Doyon A., A Transition to Sustainable Housing: Progress and Prospects for a Low Carbon Housing Future, Palgrave Macmillan, Singapore, 2025. DOI: 10.1007/978-981-99-2760-9.

[34] Sanchaniya R.J., Černeckienė J., Gudumasu N.S., Kundziņa A., "Adaptive property reuse for social housing: Benefits, challenges, and best practices," Baltic Journal of Real Estate Economics and Construction Management, vol. 13, no. 1, pp. 1–9, 2025. DOI: 10.2478/bjreecm-2025-0001.