



## **RESEARCH ON VOLUMETRIC-MODULAR RAPIDLY DEPLOYABLE HOUSING TECHNOLOGY: AN OVERVIEW OF MODERN ACHIEVEMENTS, CHALLENGES, AND PROSPECTS**

**Maxamova Maxbura**

*Lecturer of the Department of Architecture, Samarkand State Architectural and Construction University, Samarkand, Uzbekistan.*

[mahamovamahbura@gmail.com](mailto:mahamovamahbura@gmail.com)

[maxamova.maxbura@samdaqu.edu.uz](mailto:maxamova.maxbura@samdaqu.edu.uz)

<https://orcid.org/0009-0004-5089-9453>

**ABSTRACT:** This article provides a comprehensive review of current research on volumetric-modular rapidly deployable housing technology, mainly referencing publications from ResearchGate. With rising demands for efficiency, speed, and sustainability, volumetric-modular construction (VMC) presents notable advantages compared to conventional methods. Key benefits include a construction time reduction of up to 50%, an economic efficiency improvement of 20%, and better quality due to as much as 80% of work being conducted in controlled factory settings. Innovations such as Building Information Modeling (BIM) and Artificial Intelligence (AI) are transforming design and logistics, alongside advanced materials like Cross-Laminated Timber (CLT) and aerogels. However, despite its significant potential, VMC encounters systemic challenges, particularly substantial gaps in regulatory frameworks (especially concerning high-rise buildings), major transportation constraints related to module dimensions and weight, and a lack of qualified workforce. Research also suggests that the thermal properties of materials like mineral wool may deteriorate under climatic conditions, affecting long-term energy efficiency. The study concludes that while VMC stands as a highly promising and adaptable option for various scenarios, its broader implementation relies on overcoming these regulatory, logistical, and human resource challenges through coordinated efforts across the industry and ongoing scientific inquiry.

### **1. Introduction**

The contemporary construction industry faces increasing demands for efficiency, project speed, economic viability, quality, and sustainable development. In this context, rapidly deployable building technologies, particularly volumetric-modular construction, are gaining significant relevance.<sup>1</sup> Global challenges, such as rapid urbanization and the need for swift housing provision in emergency situations, as well as construction in remote or extreme climatic conditions, underscore the strategic importance of modular solutions.

Growing global demands, driven by rapid urban population growth and the imperative for swift responses to crises, not only stimulate but effectively dictate a shift towards industrialized and rapidly deployable construction methods. Traditional approaches, characterized by lengthy timelines and high resource intensity <sup>2</sup>, prove inadequate to meet current requirements. Consequently, volumetric-modular homes are transforming from an alternative option into a strategic necessity for ensuring the sustainable development of the construction sector. This shift is driven not only by a pursuit of increased efficiency, but also by a fundamental adaptation to changing conditions and the need to address basic societal needs.

Modular construction has deep historical roots and has continuously adapted to evolving societal needs. A significant impetus to its development was provided during periods that required the rapid and efficient erection of numerous buildings, such as during World War II.<sup>1</sup> In recent decades, advancements in construction technologies have focused on enhancing energy efficiency and achieving sustainable development, leading to a renewed interest in modular systems.<sup>4</sup>

The objective of this article is to systematize and analyze contemporary research in the field of volumetric-modular rapidly deployable housing technology, based on publications available on the ResearchGate platform. To achieve this goal, the following tasks were set: to clarify the terminology and classification of volumetric-modular construction systems, identify key advantages, review innovative technologies and materials, analyze structural features and operational characteristics, and identify the main challenges and prospects for the further development of this technology.

## **2. Literature Review and Methodology**

### **2.1. Definition and Classification of Volumetric-Modular Rapidly Deployable Buildings**

Buildings constructed using volumetric block modules (VBMs) represent a type of rapidly deployable building system (RDBS).<sup>4</sup> These systems are distinguished by minimal construction times, a high degree of factory readiness, technological efficiency of on-site work, and relatively low cost.<sup>3</sup> However, existing literature exhibits some terminological ambiguity. Rapidly deployable buildings are sometimes erroneously equated with volumetric modular buildings, metal-framed buildings, or structures erected using permanent formwork.<sup>4</sup>

Researchers identify several common types of RDBS, including frameless, framed (specifically, frame-monolithic), volumetric-block (modular or modular-block), core, and shell (frame-tent or frame-membrane) systems.<sup>4</sup> The main structural schemes for VBM buildings include homogeneous block, block-panel, heterogeneous block, block-panel with staggered block arrangement, frame-block, as well as schemes utilizing suspended or non-load-bearing (hanging) blocks, and block-spiral systems supported by a rigid core.<sup>4</sup>

VBM frames can be made from various materials, which determine their strength and operational characteristics. The most common types are steel frames, including light-gauge steel (LGS) and light metal structures (LMS). Wooden frames, including hollow box timber elements and cross-laminated timber (CLT), as well as reinforced concrete structures, are also employed, often forming a cap or cup.<sup>4</sup>

The existing terminological ambiguity and the absence of a comprehensive, universally accepted classification of volumetric-modular systems<sup>4</sup> pose a significant barrier to standardization, regulatory development, and consequently, to the widespread adoption and investment in this technology. Clear terminology and classification are fundamental for developing relevant building codes and standards. Without this foundation, each VBM project may require individual justification and approval, increasing costs, timelines, and risks, thereby deterring investors and slowing down mass implementation. Thus, the issue of terminology directly impacts the economic and regulatory viability of the technology.

The urgent need for a unified classification of VBM building systems is emphasized. Such a classification should consider multiple criteria, including the nature of the action, functional purpose, class, mobility, number of stories, structural scheme, VBM dimensions, materials used,

changes in overall dimensions during transportation and installation (distinguishing between transformable and non-transformable VBM), as well as durability and fire resistance indicators.<sup>4</sup>

## 2.2. Advantages of Volumetric-Modular Construction

Volumetric-modular construction offers a range of significant advantages that make it an attractive alternative to traditional methods.

**Economic Efficiency, Shorter Timelines, and Enhanced Productivity.** The factory-based production of modules is considerably quicker than traditional methods due to a controlled manufacturing setting, opportunities for process automation, and repetitive tasks. This approach enables simultaneous module production alongside foundation work at the construction site, contrasting with the sequential nature of traditional construction. Studies show that this technology can cut construction time by as much as 50% and improve economic efficiency by 20%. For instance, in the case of a two-story residential building, prefabrication can reduce the project timeline by 63 days compared to conventional approaches. Cost savings are realized by significantly lowering the requirements for formwork (up to 75%), scaffolding (75-90%), and wet concrete (90%). Additionally, lower costs stem from the high readiness level of modules at the factory, incorporating both exterior and interior finishes, which reduces the need for on-site labor. As much as 80% of all tasks can be shifted to the manufacturing location, facilitating the employment of more skilled workers and decreasing labor expenses.

**Quality Control, Waste Reduction, and Environmental Friendliness.** Factory conditions ensure significantly better quality control throughout all stages of production, resulting in a substantial reduction in defects compared to traditional construction methods.<sup>1</sup> Since most work is performed in the factory, the volume of construction waste directly on-site is considerably reduced, lowering disposal needs and associated costs.<sup>1</sup> Modular construction also contributes to a reduction in negative environmental impact, including fewer transportation cycles, which leads to a decrease in accidents and noise levels.<sup>2</sup>

**Energy Efficiency and Sustainable Development.** The use of energy-efficient materials in modular designs contributes to reduced electricity consumption during the operational phase of buildings.<sup>6</sup> Modular construction is considered a crucial factor promoting the sustainable development of the construction industry as a whole.<sup>3</sup>

The complex of advantages offered by volumetric-modular construction—speed, cost-effectiveness, quality, and environmental friendliness—is not merely a sum of individual benefits but forms a synergistic effect that transforms the entire paradigm of construction production (Fig.1). Relocating the majority of work to controlled factory environments not only reduces time and costs but also enables the implementation of stricter quality control, the use of resource-saving technologies, and waste minimization. This cumulative effect leads to significant improvements in energy efficiency and a reduction in negative environmental impact. Such a comprehensive approach, rather than just isolated benefits, positions volumetric-modular homes as a key tool for achieving sustainable development goals in the construction sector.

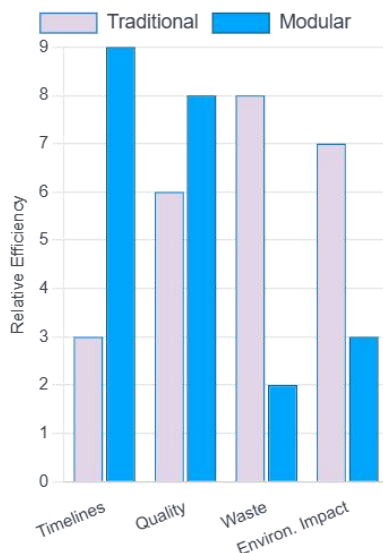


*Figure 1 Comparison of Volumetric-Modular Construction Advantages with Traditional Methods*

### 2.3. Research Methodology

This study constitutes a systematic review and analysis of scientific publications available on the ResearchGate platform. Relevant sources were identified using keywords encompassing aspects such as "volumetric-modular construction," "rapidly deployable buildings," "prefabrication," "innovative technologies," and "application in various conditions."

In selecting publications, priority was given to highly cited sources, ensuring the relevance and scientific significance of the included data.<sup>9</sup> Articles containing experimental data, numerical simulation results, literature reviews, and analyses of specific case studies of volumetric-modular technologies were also considered. Particular attention was paid to identifying structural features, technological solutions, operational characteristics, as well as existing problems and prospects for the further development of this construction methodology. This approach enabled the formation of a comprehensive understanding of the current state of research in the field of volumetric-modular, rapidly deployable homes.

## 3. Research Results

### 3.1. Innovative Technologies and Materials

**The Role of BIM Technologies and Artificial Intelligence in Design and Optimization.** The integration of digital technologies, such as Building Information Modeling (BIM) and Artificial Intelligence (AI), is fundamentally transforming the approach to designing, constructing, and operating modular buildings. BIM technologies ensure high efficiency and process synchronization by creating detailed 3D models that facilitate visualization, early detection of potential issues, and improved project understanding among all stakeholders.<sup>1</sup> In the context of modular construction, BIM enables precise planning of module production and subsequent on-site assembly, significantly reducing errors and minimizing material waste.<sup>1</sup> This technology also fosters close interaction between the design, module manufacturing, and installation phases, as any project changes are instantly reflected in the shared model accessible to all interested parties.<sup>1</sup> Furthermore, BIM allows for virtual simulations and comprehensive analyses, including energy efficiency assessment, load calculations, and checks for compliance with safety standards and structural stability, thereby optimizing building performance even before physical

construction begins<sup>1</sup>

Artificial intelligence complements BIM capabilities by optimizing the design process for modules. It analyzes vast amounts of data from previous projects, proposing optimal solutions for module geometry, placement, load-bearing capacity, and energy efficiency, which substantially reduces design time and costs.<sup>1</sup> AI also finds application in planning and logistics, analyzing variables such as production capacity, resource availability, and delivery/assembly conditions to develop the most efficient work plans.<sup>1</sup> In the module production process, AI systems enhance quality control, overall efficiency, and shorten production cycles, directly impacting the reduction of the final product cost. AI can also optimize production processes and contribute to the implementation of lean construction principles by analyzing employee movements.<sup>1</sup> On the construction site, AI, integrated with drones and autonomous robots, improves the accuracy of module installation and reduces risks for workers.<sup>1</sup>

**Application of New Construction Materials.** The development of volumetric-modular construction is closely linked to the introduction of innovative materials that improve operational characteristics and expand architectural possibilities.

- **Cross-Laminated Timber (CLT):** This material, composed of layers of timber glued perpendicularly to each other, possesses high strength, making it an ideal choice for use as load-bearing elements in walls, floors, and roofs of modular buildings. Its excellent thermal insulation properties and relatively low weight simplify transportation and contribute to reduced energy consumption for heating and cooling buildings.<sup>1</sup>
- **Aerogels:** These are ultra-light materials with outstanding thermal insulation properties. They serve as a highly effective insulation layer in modular structures, significantly reducing heat loss without requiring an increase in wall thickness.<sup>1</sup> In combination with nanomaterial-based thermal insulation, aerogels contribute to reducing the building's overall energy consumption and carbon emissions.<sup>1</sup>
- **Composite Materials:** Increasingly applied in modular design, as they allow for combining the best qualities of metal, plastic, and wood. These materials are lightweight, strong, resistant to corrosion, rot, moisture, and other aggressive environmental factors, ensuring the creation of durable, reliable, and aesthetically appealing modular elements.<sup>1</sup>
- **Recycled Materials:** Modular construction technology actively supports the use of building materials produced in accordance with principles of ecological compatibility and sustainability. Materials from recycled raw materials, such as recycled plastic and rubber, not only reduce waste but also enhance the overall environmental value of modular construction, finding application as insulation boards, flooring, and other building elements.<sup>1</sup>

The synergy between digital technologies (BIM, AI) and innovative materials (CLT, aerogels, composites) is a key factor in overcoming traditional limitations of modular construction, such as architectural monotony and optimization complexities. Digital tools enable the most efficient use of new materials' potential, for example, optimizing module geometry for CLT use or precisely calculating layers with aerogels. Artificial intelligence can generate unique architectural solutions, overcoming the problem of "architectural monotony"<sup>6</sup>, while utilizing the properties of composites to create complex forms. This leads to the creation of more complex, functional, and sustainable structures that would be impossible or inefficient to achieve using traditional methods and materials (Fig. 2).

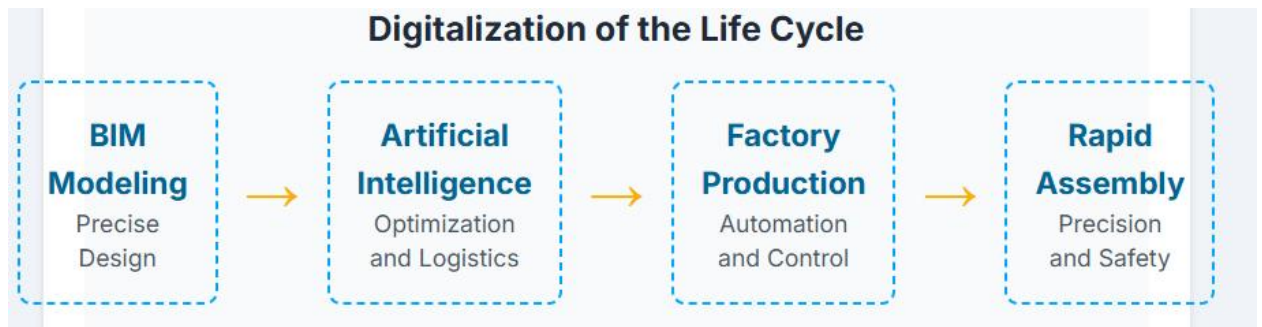


*Figure 2 Drivers of Innovation: Technologies and Materials*

### 3.2. Structural Features and Nodal Connections

**Types of Volumetric Block-Module Frames.** As noted, VBM frames can be made of steel, timber, or reinforced concrete. The choice of frame material depends on specific requirements for strength, weight, thermal performance, and building operating conditions.<sup>4</sup> Each material type offers unique advantages, allowing modular designs to be adapted to a wide range of applications.

**Overview and Analysis of Common Horizontal and Vertical Nodal Connections.** The quality and type of nodal connections mainly used determine the efficiency and reliability of modular construction. The most common connection for horizontal and vertical joints in 3D modular blocks is the "tongue and groove" type.<sup>12</sup> This type of connection ensures high assembly precision and structural strength.

In addition to "tongue and groove," other types of connections are also employed:

- **Threaded connections:** These involve the use of bolts, studs, and nuts for module fixation. For example, horizontal module connections can be achieved with reinforced bolts and reinforced lock nuts.<sup>12</sup> Reinforced eye bolts are also frequently used.<sup>12</sup> Metal plates are installed at the joints, and typical details of these plates for fastening modular blocks include floor, ceiling, bolt fastening, tie, and support plate elements.<sup>12</sup>
- **Internal and external tie bolts:** When assembling single-level VBM systems, modules are connected using internal and external tie bolts. This is characteristic of VBMs made from shipping containers, where bolts are installed in container fittings, and internal bolts are tightened with clamps.<sup>12</sup>
- **Twistlock fasteners:** Used for connecting container-type volumetric blocks and installed in standard shipping fittings.<sup>12</sup>
- **Special corner cones:** Applied for connecting two or more levels of modular systems, preventing module displacement.<sup>12</sup>
- **Special tension ties:** Along the facade perimeter of multi-level buildings, lower and upper volumetric blocks are connected using special tension ties.<sup>12</sup>

**Innovations in Nodal Connections.** Technological advancements have led to the emergence of innovative connection systems, such as the Modular Integrating System (MIS) and the VectorBloc multi-functional fastening. These systems, also based on the "tongue and groove" principle, provide both horizontal and vertical structural connections.<sup>12</sup> MIS enables the fabrication of finished modules with fastening elements, both in the factory and on the construction site. To create a unified structure, connecting strips with tenons and grooves are installed along the entire perimeter of the upper and lower parts of the module. One strip from each module in each direction connects with the strips of adjacent modules.<sup>12</sup>

In MIS, tenons are located on the upper corner fastenings of the modules, and grooves are on the lower ones. Horizontal connection of VBMs is achieved by placing connecting plates (strips) over the tenons and securing them with bolts. For vertical connection of VBMs, upper-tier modules are positioned so that the tenons of the lower-tier VBMs align with the grooves of the upper-tier VBMs, ensuring centering of the two tiers. The VBMs are then tightened with bolts, forming an angular connection of four blocks across two tiers. This fastening method allows modules to be stacked and joined to create fully reinforced buildings of almost any shape.<sup>12</sup>

Scientific publications also propose a horizontal connection of metal frames in volumetric modular blocks using "tongue and groove" technology, featuring sigma-shaped protrusions (tenons) and grooves. These connecting parts are installed along the perimeter of the combining blocks, with some having protrusions and others grooves.<sup>12</sup> Vertical connection in MIS is achieved using locking clamps and L-shaped elements that have sigma-shaped protrusions (tenons) and grooves in both vertical and horizontal directions. These are installed along the perimeter of the upper parts of the first-tier VBMs and the lower parts of the last-tier VBMs, and on middle tiers, they are on both the lower and upper parts of the building's VBMs <sup>12</sup>

**Ensuring Strength, Rigidity, and Installation Manufacturability.** The efficiency of modular construction largely depends on the nodal connections used.<sup>12</sup> Volumetric block modules are inherently strong structures, but their combined performance as part of a unified building system requires rigid horizontal connections to ensure reliable and long-term operation.<sup>12</sup> This implies that all VBMs must be securely connected both horizontally and vertically. The necessary degree of strength and rigidity of plywood load-bearing elements with "tongue and groove" connections has been confirmed by transverse bending tests.<sup>13</sup>

The development and optimization of nodal connections, from simple bolted joints to innovative systems like MIS, are critical factors determining not only the structural integrity and durability of volumetric-modular buildings but also their manufacturability during installation and the speed of erection on-site. This directly impacts the economic attractiveness and competitiveness of modular construction. Advanced nodal connections significantly reduce installation time and labor, enhance assembly precision, and ensure the necessary strength and rigidity of the entire structure. Without reliable and technologically efficient connections, the advantages of factory fabrication could be negated by the complexity and inefficiency of on-site assembly (Tab.1).

**Table 1: Overview of Common Nodal Connections for Volumetric Block-Modules**

| Connection Type               | Description and Application                                                                         | Advantages                                       | Source |
|-------------------------------|-----------------------------------------------------------------------------------------------------|--------------------------------------------------|--------|
| "Tongue and Groove"           | Most common for horizontal and vertical joints of 3D modules.                                       | High assembly precision, strength.               | 12     |
| Threaded (bolts, studs, nuts) | Horizontal module connection, fixation with reinforced bolts and lock nuts. Metal plates at joints. | Reliable fixation, possibility of reinforcement. | 12     |

|                                                      |                                                                                                 |                                                                                                          |    |
|------------------------------------------------------|-------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------|----|
| <b>Internal and External Tie Bolts</b>               | For single-level systems, especially for VBMs from shipping containers.                         | Ease of installation, characteristic of container structures.                                            | 12 |
| <b>Twistlock Fasteners</b>                           | For connecting container-type VBMs, installed in standard fittings.                             | Rapid connection, standardization.                                                                       | 12 |
| <b>Special Corner Cones</b>                          | For connecting two or more system levels, prevent module displacement.                          | Prevents displacement, ensures centering.                                                                | 12 |
| <b>Special Tension Ties</b>                          | Along the facade perimeter of multi-level buildings.                                            | Ensures overall rigidity and stability.                                                                  | 12 |
| <b>Modular Integrating System (MIS) / VectorBloc</b> | Innovative "tongue and groove" based systems for horizontal and vertical structural connection. | High installation manufacturability, allows for complex shapes, factory readiness of fastening elements. | 12 |

### 3.3. Operational Characteristics and Testing

**Thermal Properties of Enclosing Structures and the Influence of Climatic Factors.** The energy efficiency of a building is largely determined by the thermal characteristics of its enclosing structures, particularly wall panels.<sup>14</sup> These characteristics directly influence the indoor microclimate, heating and cooling costs, and overall comfort of living and working in the building.<sup>14</sup>

Experimental studies have shown that climatic factors can influence the thermal properties of materials used in modular building wall panels. For example, for mineral wool wall panels, an increase in thermal conductivity from 0.037 W/m·K to 0.04 W/m·K (an 8% increase) and a decrease in thermal resistance by 3% (from 2.76 to 2.67 m<sup>2</sup>·K/W) were recorded after exposure to climatic factors.<sup>14</sup> These changes are typically associated with moisture absorption by the material and its structural degradation. The deterioration of thermal insulation properties leads to increased heating costs and reduced building energy efficiency over its lifespan, especially in regions with harsh climates.<sup>14</sup>

**Research on Seismic Resistance and Durability of Volumetric-Modular Structures.** VBM construction systems demonstrate high resistance to static, dynamic, cyclic, and seismic loads.<sup>6</sup> This makes them a promising solution for construction in seismically active regions. However, to ensure safety and reliability, further development of the regulatory framework is necessary. Specifically, national standards for testing modules for seismic effects are required, especially for reinforced concrete modules.<sup>15</sup> The durability of VBM buildings directly depends on the correct selection of materials and, equally importantly, on the reliability and quality of nodal connections.<sup>7</sup>

**Application of Experimental and Numerical Modeling Methods.** Both numerical and

experimental methods are actively used for the comprehensive evaluation and optimization of volumetric-modular structures. Numerical and computer modeling, including information modeling and computational materials science, are applied to analyze the stress-strain state, dynamics, and stability of building structures at various stages of their life cycle. These methods enable the prediction of the behavior of structures under various loads and impacts.

Experimental studies play a key role in confirming theoretical propositions and modeling results. For instance, experimental studies have been conducted to confirm theoretical provisions regarding the strength, crack resistance, and deformability of reinforced concrete elements reinforced with composite materials.<sup>16</sup> Digital technologies are also actively used in field studies, such as laser scanning for precise surveying of existing buildings and monitoring of load-bearing structures using geodetic measurements and seismometric methods.<sup>11</sup> The seismometric method enables a comprehensive inspection of a building and the detection of significant changes in load-bearing structures without requiring direct instrumental intervention or visual inspection of each component. It achieves this by determining natural frequencies and vibration modes, which can indicate localized damage.<sup>11</sup>

Despite the generally high resistance of volumetric-modular structures to extreme loads, such as seismic impacts, their long-term operational efficiency, particularly concerning thermal performance, remains vulnerable to climatic factors.<sup>14</sup> This indicates the necessity not only for further research in materials and connections but also for developing comprehensive design approaches that account for the dynamic change in material properties over the life cycle to ensure stated energy efficiency and durability. There is a dissonance between the high structural reliability of VBMs in extreme conditions and their potential vulnerability to ordinary climatic influences, affecting their operational characteristics. This means that to ensure true VBM durability and sustainability, strength alone is insufficient; a deep understanding and compensation for changes in material properties, especially insulation, throughout the building's life cycle are required. This necessitates a more integrated approach to materials science and design, as well as the development of new standards for assessing long-term operational performance.

### 3.4. Application Specifics in Various Conditions

**Specifics of Construction in Far North Conditions.** The application of volumetric-modular technologies in the Far North demonstrates significant economic and environmental advantages.<sup>6</sup> VBMs exhibit high resistance to static, dynamic, cyclic, and seismic loads, as well as high installation manufacturability, which is critically important in conditions of a limited construction season.<sup>6</sup>

However, construction in these regions presents unique challenges, including extremely low temperatures, high humidity, strong wind loads, and the presence of permafrost.<sup>6</sup> There are also serious transportation limitations related to the large dimensions and weight of VBMs. According to Russian road traffic regulations, oversized cargo should not exceed 12 m in length, 2.55 m in width, and 4 m in height from the road surface.<sup>8</sup> Meanwhile, Chinese researchers note that VBMs can reach 5.7 m in width and 12 m in length, and modules easily transportable without significant difficulty typically have a width of less than 4.5 m and a length of up to 13 m.<sup>6</sup> Vibrations during transportation can lead to a reduction in the stated strength of some VBM components, with the degree of damage depending on the road category.<sup>6</sup>

To overcome these difficulties, the following solutions are proposed: the use of lightweight VBMs, equipping vehicles with vibration dampeners (though this increases cost), and considering specific principles of construction on permafrost. The latter includes either

preserving frozen ground throughout the building's lifespan (e.g., using ventilated crawl spaces) or, conversely, thawing it with the use of pile foundations or concrete column foundations.<sup>6</sup>

Architectural requirements for Arctic construction also have their specific features: it is important to consider local experience, prioritize rounded forms that are less susceptible to wind and seismic loads, and use compact buildings with a closed contour and minimal open spaces. Smooth exterior surfaces help reduce snow accumulation. Buildings should have double vestibules at entrances and a minimal number of entry/exit points, while adhering to evacuation requirements. For facades, bright colors are recommended, considering the local landscape<sup>6</sup>

**Development of High-Rise Modular Construction.** Modern construction technologies allow for the erection of not only low-rise but also multi-story, high-rise, and even unique, rapidly deployable buildings. An example is a 57-story skyscraper built in 19 days using prefabricated modules with a high degree of factory readiness.<sup>3</sup>

However, the development of high-rise modular construction faces several significant limitations. One of the main barriers is the lack of an adequate regulatory framework. The existing GOST R 58760–2019 standard, which regulates modular block containers, does not apply to buildings taller than three stories, forcing companies to prove the load-bearing capacity of the module's frame for each specific case that falls outside the standard.<sup>1</sup> This leads to increased time and costs for design and approval. Furthermore, there is a lack of experience and knowledge among specialists, as well as a shortage of skilled labor in modular construction, which hinders the full realization of the technology's potential.<sup>10</sup> Additional transportation costs, which can reach 18% of the total project cost, and difficulties in ensuring the required fire resistance are also significant obstacles.<sup>10</sup>

**Application of Modular Structures for Temporary Housing.** Modular structures play a crucial role in providing temporary housing, particularly in emergency situations and following natural disasters.<sup>5</sup> In this context, two main types of temporary housing are distinguished:

- **Prefabricated components:** Easily transportable and can be erected by local residents or volunteers.<sup>5</sup>
- **Ready-made structures (prefabricated structures):** Can be immediately integrated in emergency situations, but their transportation is more complex.<sup>5</sup>

The application of volumetric-modular technologies in extreme conditions (e.g., the Far North) and for high-rise construction demonstrates that, while the technology possesses high adaptability, its successful implementation critically depends on overcoming logistical (transportation) and regulatory barriers, as well as on developing specialized design and material science solutions for unique conditions. This underscores that "rapid deployability" is not a universal property, but rather requires a deep adaptation to the context. The potential of VBMs in complex conditions cannot be realized without addressing external infrastructural and legal issues. In such cases, "Rapid deployability" becomes not just a matter of technology but also a matter of systemic readiness, encompassing transport infrastructure, regulatory frameworks, and the availability of qualified personnel. Thus, the success of VBMs in specific conditions depends not only on internal technological improvements but also on external factors requiring a comprehensive approach.

#### 4. Discussion

#### Comprehensive Analysis of the Realization of Volumetric-Modular Construction

## Advantages

Volumetric-modular construction, as demonstrated in the results section, offers significant advantages over traditional methods, including reduced timelines (up to 50% <sup>1</sup>), lower costs (up to 20% <sup>2</sup>), enhanced quality through factory control <sup>1</sup>, minimized waste <sup>2</sup>, and improved environmental performance.<sup>6</sup> These benefits are not isolated but interconnected, forming a holistic system for efficient and sustainable construction. The high degree of factory readiness <sup>3</sup> allows for the transfer of up to 80% of labor-intensive work to a controlled environment <sup>1</sup>, leading to increased productivity and reduced dependence on weather conditions.

Despite the obvious and quantitatively confirmed advantages of volumetric-modular structures, their full potential and widespread adoption are hindered not so much by the technological limitations of the modules themselves, but by external systemic factors. These factors include an outdated regulatory framework, logistical complexities, and a shortage of qualified personnel. If the technology itself is efficient, but its implementation is difficult, this indicates that the problem lies outside the technology itself. These are not merely "challenges," but systemic "impediments" that prevent the industry from fully utilizing existing technological achievements. This highlights the need to shift from localized technological innovations to a comprehensive transformation of the entire construction ecosystem. Thus, the discussion should move from questions about whether volumetric-modular construction can be effective to questions about what prevents its widespread adoption, emphasizing the need for macro-level reforms.

## Identification and Analysis of Key Challenges and Limitations

**Regulatory and Standardization Gaps.** A major obstacle to modular construction is the lack of modern and comprehensive regulatory documents. The current GOST R 58760–2019, which governs modular block containers, does not extend to buildings higher than three stories. This limitation creates legal and engineering issues, requiring developers to individually demonstrate the load-bearing capacity of each module. Consequently, the design and commissioning process is significantly delayed. There is an urgent need for new standards, particularly for testing loading and seismic effects in reinforced concrete modules.

**Transportation and Logistics Complexities.** The large dimensions and significant weight of volumetric block-modules <sup>8</sup> substantially limit the choice of transport vehicles and delivery routes.<sup>6</sup> This leads to increased transportation costs, which can account for up to 18% of the total project cost.<sup>10</sup> Furthermore, vibrations occurring during transportation can negatively affect the stated strength of module components.<sup>6</sup>

**Shortage of Qualified Specialists and Experience.** The lack of sufficient experience and knowledge, as well as a deficit of skilled labor, are serious obstacles throughout the entire life cycle of modular construction.<sup>10</sup> This impacts the quality of design, production efficiency, and installation accuracy, ultimately increasing project timelines and costs.

**Architectural Monotony.** In public perception and among some specialists, there is a notion of architectural uniformity and limited forms for buildings constructed from VBMs.<sup>6</sup> Although modern technologies, such as BIM and AI, as well as new materials, allow for the creation of customized and complex architectural solutions <sup>6</sup>, this perception remains a hindering factor.

**High Initial Investments.** The establishment and modernization of production facilities for large-scale modular construction require significant initial capital investments.<sup>1</sup> This can be a barrier to market entry for new companies and hinder industry development.

## Comparative Analysis of Volumetric-Modular Construction with Traditional Methods

**Speed:** Modular construction significantly surpasses traditional methods in terms of erection speed. This is achieved through the parallelism of factory production processes and on-site work, which shortens overall project timelines.<sup>1</sup>

**Cost:** In general, modular buildings, especially typical projects, can be cheaper than traditional counterparts.<sup>1</sup> However, high initial investments in establishing production facilities can be a significant barrier to the widespread adoption of the technology.

**Quality:** Factory control ensures higher and more consistent quality of modules, reducing the number of defects that often arise in traditional on-site construction.<sup>1</sup>

**Environmental Friendliness:** Modular construction is characterized by significantly less on-site waste and a reduced overall carbon footprint due to optimized processes and the use of recycled materials.<sup>1</sup>

**Labor Input:** Transferring most of the work to the factory reduces the need for on-site labor. However, this requires more qualified personnel in production, highlighting a shift in the industry's workforce requirements.<sup>1</sup>

## Prospects for Development and Key Directions for Further Scientific Research

The outlook for the advancement of volumetric modular construction seems promising, particularly due to continuous technological innovations and a growing focus on sustainable development.

- **Technological Innovations:** Further integration of BIM and AI will revolutionize modular construction, enhancing project accuracy, efficiency, and sustainability.<sup>1</sup> This includes developing more sophisticated algorithms for optimizing design, logistics planning, and automating production processes.
- **New Materials:** Further research is needed in the field of composite materials, as well as lightweight and energy-efficient solutions to lighten structures and improve their operational properties, especially in extreme climatic conditions.<sup>6</sup>
- **Nodal Connections:** The development of advanced solutions for nodal connections is a critically important task. These solutions must ensure high installation manufacturability, reliable and long-term operation, as well as resistance to dynamic and seismic loads.<sup>6</sup>
- **Regulatory Framework:** There is an urgent need to develop and improve regulatory documents for modular construction. These documents should cover the entire life cycle of modular buildings and all their types, including multi-story and high-rise structures, and account for the specifics of various climatic zones.<sup>6</sup>
- **Classification:** Completing the development of a comprehensive classification scheme for VBM buildings and structures, considering all key parameters, will contribute to industry standardization and systematization.<sup>4</sup>
- **Human Capital:** The development of educational programs and initiatives to enhance the qualifications of engineers, architects, and workers in modular construction is a fundamental condition for overcoming the shortage of skilled personnel.<sup>10</sup>

**Table 4: Main Challenges and Solutions in Volumetric-Modular Construction**

| Challenge | Solutions / Ways to Overcome | Source |
|-----------|------------------------------|--------|
|-----------|------------------------------|--------|

|                                                            |                                                                                                                                                                                         |    |
|------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| <b>Gaps in Regulatory Framework</b>                        | Prioritized development and harmonization of national and international standards (GOSTs) for all types and heights of modular buildings, including testing methods (loading, seismic). | 1  |
| <b>Transportation and Logistics Complexities</b>           | Modernization of production facilities for lightweight VBMs; use of vehicles with vibration dampeners; optimization of logistics routes using AI.                                       | 6  |
| <b>Shortage of Qualified Personnel and Experience</b>      | Development of educational programs and initiatives for upskilling engineers, architects, and workers in modular construction.                                                          | 10 |
| <b>Architectural Monotony</b>                              | Active development and implementation of BIM/AI for design optimization and creation of architecturally unique and complex forms.                                                       | 1  |
| <b>High Initial Investments</b>                            | Stimulation of investments through government support programs, development of leasing schemes for equipment.                                                                           | 1  |
| <b>Difficulties in Ensuring Fire Resistance</b>            | Further research and development of fire resistance standards for modular structures.                                                                                                   | 10 |
| <b>Influence of Climatic Factors on Thermal Properties</b> | Research into new materials and technologies to enhance the durability of thermal insulation properties (e.g., protection against moisture absorption and structural degradation).      | 14 |
| <b>Lack of Comprehensive Classification</b>                | Development of a unified classification scheme for VBMs.                                                                                                                                | 4  |

## 5. Conclusion

### **\*\*Main Findings from the Review\*\***

The review of research shows that volumetric-modular construction stands out as a highly promising and economically efficient method within today's construction sector. It provides considerable advantages compared to traditional techniques, such as faster construction times, enhanced quality through factory oversight, reduced construction waste, and improved environmental performance.

Innovative technologies, including Building Information Modeling (BIM) and Artificial Intelligence (AI), along with the use of new materials like cross-laminated timber, aerogels, and various composites, are essential for broadening the potential of volumetric-modular structures. These developments allow for the design of more intricate, energy-efficient, and architecturally unique buildings, addressing past limitations.

The advancement and optimization of nodal connections are vital for maintaining the structural integrity, stability, and manufacturability of modular systems during installation. Reliable connections are key for the long-term safety and functionality of buildings, facilitating the advantages of factory production.

The use of volumetric-modular technologies in extreme climatic conditions, such as those in the Far North, and for high-rise developments showcases their remarkable flexibility and potential.

Nevertheless, it also exposes systemic challenges, including logistical issues related to module size and weight, and significant gaps in the current regulatory framework. These external factors necessitate comprehensive solutions that go beyond mere technological advancements.

### **Recommendations for Stimulating the Development and Widespread Adoption of Volumetric-Modular Rapidly Deployable Housing Technology**

To ensure the ongoing sustainable development and widespread adoption of volumetric-modular rapidly deployable housing technology, coordinated efforts are essential in several key areas:

1. **Prioritized Development and Harmonization of Standards:** Accelerating the process of developing and harmonizing national and international standards and regulatory documents that encompass all types and heights of modular buildings is crucial. This includes creating clear methodologies for testing loading, seismic effects, and durability.
2. **Investment in Infrastructure:** Investments in modernizing production facilities for modular construction and developing logistical infrastructure capable of efficiently handling the transportation of large modules must be promoted. This may involve developing specialized transport vehicles and optimizing routes.
3. **Human Capital Development:** The development and implementation of educational programs and initiatives to upskill engineers, architects, designers, and workers specializing in modular construction are vital for addressing the shortage of qualified specialists and ensuring high-quality project execution.
4. **Continued Scientific Research:** Further scientific research is required in the field of new materials, particularly regarding their durability and resistance to climatic factors (e.g., moisture absorption). It is also important to continue optimizing nodal connections to enhance their reliability and manufacturability, as well as examining the long-term operational characteristics of modular buildings under various conditions.
5. **Active Implementation of Digital Technologies:** Actively promoting and supporting the implementation of digital technologies, such as BIM and AI, at all stages of the life cycle of modular buildings should be encouraged. This will improve the efficiency of design, production, installation, and operation, while also reducing risks and costs.

The implementation of these recommendations will help overcome existing barriers and fully realize the potential of volumetric-modular construction, contributing to the development of a more efficient, sustainable, and adaptive construction industry.

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