Sustainability of construction based on digital and modular technologies

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Abstract. The XXI century has confronted humanity with a number of global environmental and social problems. Some of them depend on the construction industry. The tasks of ensuring the sustainability of construction have become relevant. The article discusses modular construction as one of the most promising ways to achieve the requirements of sustainable construction. The purpose of the study is to analyze the prospects for the implementation of modular construction technology based on modern digital technologies to achieve the objectives of sustainable construction. The analysis of modular construction materials is carried out. The main advantages of using modular technologies (efficiency, quality, speed, environmental friendliness) are determined. Increasing the degree of automation and the introduction of modern digital technologies is a promising direction for the development of modular construction. It is noted that the promising areas of production automation are robotic machines, manipulators and 3D printers. It is noted that the use of BIM technologies is necessary to automate the design process. The digital information model allows to collect all the information about a modular object and its components and to use it at all stages, including the manufacture of structures. Generative design in combination with BIM allows to automate the synthesis of design solutions according to specified requirements. As a result of the research, a scheme for integrating BIM, generative design and modern factory production facilities into a single digital production chain of modular construction is proposed. Such chain is a bundle of a virtual conveyor of information models based on generative design and a factory production system with the use of 3D printing to manufacture structures according to the specifications of the information model. The system of synthesis of design solutions on the base of the system of generative algorithms is proposed. Examples of local optimization problems of generative design for modular construction are presented. The conclusion is made about the need for a comprehensive application of the considered technologies to achieve the greatest efficiency of construction.

Keywords: modular construction, building information modeling, generative design, additive manufacturing, sustainable construction.
1 Introduction

In recent decades, humanity has faced several global problems of a natural and social nature, solutions to which are being sought by scientists around the world. Environmental pollution, climate change, the energy crisis, as well as demographic problems and unprecedented rates of urbanization threaten the sustainable development of future generations. The urban environment is one of the main sources of these problems, so the responsibility for solving these problems lies largely with the construction industry. In this regard, issues of sustainability of construction come to the fore, which often mean the level of requirements that must be achieved within a separate construction object, for example, energy efficiency, environmental friendliness, economy or ergonomics [1, 2]. Thus, more and more attention is paid to the development of technologies that contribute to achieving these new requirements. One of the possible ways to achieve efficiency in the construction sector is the mass introduction of modular construction technologies using innovative design and production methods.

Modular technologies are based on the principle of dividing the system into independent parts – modules. This approach of system design makes it possible to increase its efficiency, since modules can be produced independently of each other, and repeatedly used in various configurations depending on the required characteristics of the system [3]. Due to this, it becomes possible to remove, add or replace individual modules in the system, which ensures multi-variant design, its high stability, ease of maintenance and repair, as well as overall efficiency [4].

All these principles are also used in modular construction, which is engaged in the development, production and construction of modular buildings. The basis of the constructive solution of such buildings are block modules, which are autonomous large-dimensional layout spatial space-planning elements of the building, manufactured, as a rule, in factory production conditions outside the construction site. Such modules, assembled or disassembled, are transported to the construction site, where a full-fledged building is assembled from them in the shortest possible time, as from a construction kit [5].

Thus, the researchers identify three significant indisputable advantages of using modular technologies in construction:

• cost–effectiveness of production – It is ensured by optimal consumption of building materials, reduced labor intensity of work, a high degree of automation and standardization, as well as minimizing adverse impacts on the construction site;
• the speed of construction – It is provided by a significant reduction in the time of construction and installation work due to factory production conditions;
• high quality solutions – It is provided by optimal factory conditions, the use of high-precision factory equipment and minimizing adverse impacts on the construction site [6].

In addition, the modern level of development of modular construction technologies allows us to achieve some important positive effects:

• environmental friendliness – Factory production allows you to control the volume of production waste, and the use of environmental materials reduces the impact on the environment. After the expiration of the service life, the modular building can be disassembled and recycled;
• mobility - Modular construction makes it possible to reach places with insufficiently developed infrastructure and transport to any place and installation in cramped and unfavorable conditions;
• multivariance and adaptability – The produced modules can be assembled in various configurations and can adapt the building to specific conditions;
• low labor intensity of work - Standardization of work processes and maximum mechanization of all work in factory conditions contribute to reducing the labor intensity of work;
• safety – Factory conditions allow you to monitor the health of workers and occupational safety [7].

Modular technologies are already actively used in many developed countries. Thus, European studies show that modular factory buildings with a number of floors from 3 to 6 floors, built using environmentally friendly building materials, are the most effective in terms of energy efficiency, environmental friendliness and safety [8].

Today modular technologies are becoming one of the most promising areas of the global construction industry and are actively developing in many countries. One of the main trends in the development of modular construction is an increase in the degree of mechanization and automation of the production process, contributing to the efficiency of modular construction. This shows that the future of modular construction is inextricably linked with the use of modern digital technologies.

The purpose of the work is to explore the prospects for the implementation of modular construction technology based on the integrated application of modern digital technologies to achieve sustainable construction objectives.

2 Materials and methods

2.1 Module manufacturing technologies

Modular prefabricated construction is usually associated with the technologies of pre-factory manufacturing of modular components. The essence of this concept is to transfer the maximum amount of labor-intensive work to the factory workshops and minimize work on the construction site [9]. Depending on the structure of the building and the degree of factory readiness of components, both individual structures (frame-panel construction) and full-fledged large-sized high-readiness block modules with integrated engineering networks and finished decoration (volumetric modular construction) can be delivered from the factory to the construction site. The higher the readiness of the modules, the less time and resources will be needed for the construction of the building.

To automate the factory production of modules, numerical control machines are used for high-precision mechanized manufacturing of structures [10]. Advanced enterprises use robotic manipulators widely used in mechanical engineering to assemble modules. This solution makes it possible to increase the level of automation of production, significantly increasing productivity, quality and reliability of products, as well as improve occupational safety. In addition, the urgency of the problem of lack of working resources, which is associated with the unwillingness of people of the new generation to work in hazardous production, is noted. Robotic modular construction is one of the solutions to this problem [11].

In addition, modular construction is a promising direction for the introduction of additive manufacturing technology (3D printing). This is due to the relative compactness of the module (as a rule, its dimensions are limited by transportation conditions and do not exceed 100 m²). In this regard, large-sized expensive 3D printing installations will not be required for 3D printing of a modular building. In combination with modern eco-materials, this technology can significantly reduce emissions of harmful substances during the production and operation of buildings, increasing their eco-efficiency [12]. In addition, 3D printers allow you to create structures of non-standard shape optimal in strength with minimal weight and material consumption, designed using generative algorithms.
2.2 BIM technologies

The modern process of designing any buildings is based on information modeling technology. The building information model is a complex object-oriented model of a construction object, which is based on a digital 3D model and information related to its elements about the geometric, physical and functional characteristics of a construction object throughout its life cycle. The use of the information model can significantly improve the design efficiency due to high interactivity and object-orientation, as well as due to the possibility of detecting all possible potential problems of the object already at the design stage. The information model itself can serve as a basis for further analysis and calculations, as well as for the use of various digital technologies [10, 13-16].

In the case of a modular object, design, as a rule, should begin with determining the modular structure of the building and creating a file structure of information models of individual modular units designed considering their functional and geometric interconnectedness. The resulting information models form a library of standardized building elements, from which a model of the entire building or its individual components (floors, sections, blocks, etc.) is then assembled. Thus, individual information models form a common hierarchically interconnected multilevel information model. The system of principles for the formation of such a model from modules of maximum readiness, considering all possible factors, is described in detail in [3].

2.3 Generative design technology

Generative design helps architects in the decision-making process by generating and analyzing a variety of project options to create a small sample of the most effective variations for practical research. The use of this technology allows designers to consider a wider space of possible solutions in less time, stimulating the creative design process [10]. Similarly, as robotic machines form a conveyor for the production of an unlimited number of modular structures, the generative design algorithms make it possible to form a virtual conveyor for the creation of information models of a modular building, thereby increasing the degree of automation of production (Fig. 1).

Fig. 1. Automated design with generative algorithms and automated manufacturing with robotic conveyors.

Generative design is an innovative design and design method based on the generation of parametric and generative models [17] according to a predetermined set of mathematical algorithms. Unlike traditional design methods, this technology allows you to expand the role of computer technology in the development of projects.
The generative design system is conditionally divided into a synthesis subsystem and an analysis and optimization subsystem. The first subsystem contains shaping algorithms that define the rules according to which the generation of design solutions is performed. The second subsystem evaluates the effectiveness of the generated options according to the specified criteria, goals and constraints, as well as the selection of the most effective solutions. To do this, generative design systems use optimization algorithms, for example, genetic algorithms based on the principles of biological evolution or neural networks.

An example of the use of generative technologies for sustainable construction is the EcoGen software product developed by a team of French researchers [18]. This software product explores the energy, atmospheric, functional and structural factors of eco-efficient building design at the early stages of design using a generative and multi-criteria approach. The evaluation mechanism places the generated solutions in the climatic environment, and then makes calculations that take into account economic, energy and environmental factors. The program allows you to calculate and optimize the parameters of light comfort, evaluate the potential of placing solar panels on the roof or facade. It is possible to consider the compactness of the building to reduce the economic cost of the project, to evaluate the thermal characteristics to avoid overheating in summer on the basis of numerous models for various climatic conditions. After the algorithm is completed, the architect can interactively explore the best solutions according to various criteria using appropriate indicators.

Generative design technology can be implemented in modular construction at the local level to optimize individual structural elements. But for the greatest effect, generative design should be used to solve more global problems: generating full-fledged information models of modular buildings according to efficiency criteria (structural-parametric synthesis of the modular building information model) [19, 20].

3 Results

As a result of the study, a scheme for the use of modular construction based on digital technologies is proposed, which allows integrating the production process of a modular building into a continuous digital production chain (Fig. 2).

Such chain includes a system for synthesizing design solutions based on generative design and a system of automated factory production using robotics and additive manufacturing technology. These systems are united using an information model with a hierarchical file structure based on a library of modular units.

![Fig. 2. Digital production chain of modular construction.](https://example.com)

For a multi-storey modular building of sectional type, the structure of the information model is presented (Fig. 3). In this structure, each modular element: a block module, a
floor, a section is a separate parametric information model with the possibility of repeated use at various levels of the hierarchical structure of the building.

![Diagram of hierarchical file structure of information models of a residential building of sectional type.](image)

Fig. 3. Diagram of the hierarchical file structure of information models of a residential building of sectional type.

The proposed system of structural-parametric synthesis of design solutions uses a set of generative algorithms and operates with parametric information models of a modular building. At the same time, the most effective solutions are selected.

When designing a modular building of sectional type, various optimization tasks can be solved at its various levels. Table 1 shows examples of local optimization problems of generative design in construction, their objectives and efficiency criteria that can be achieved as a result of the solution.

**Table 1.** Examples of local optimization problems of generative design for modular construction.

<table>
<thead>
<tr>
<th>Local optimization problem</th>
<th>Objective</th>
<th>Efficiency criterion</th>
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<tbody>
<tr>
<td>Utilization of the construction site</td>
<td>Optimal location of building sections on the construction site</td>
<td>Economy</td>
</tr>
<tr>
<td>Automatic assembly of project information models</td>
<td>Arrangement of modules in the project according to their geometric and functional relationships</td>
<td>Design speed, flexibility of design solutions</td>
</tr>
<tr>
<td>Preliminary calculation of stresses</td>
<td>Minimizing stresses in load-bearing structures</td>
<td>Reliability</td>
</tr>
<tr>
<td>Increasing of energy efficiency</td>
<td>Minimizing the area of the building outer shell</td>
<td>Economy, energy efficiency</td>
</tr>
<tr>
<td>Calculation of solar illumination</td>
<td>Minimizing overheating of the building in the summer and ensuring the best natural illumination of the premises</td>
<td>Energy efficiency, ergonomics</td>
</tr>
<tr>
<td>Generation of apartment planning</td>
<td>Maximization of useful living space, distribution of apartment areas according to demographic or economic parameters</td>
<td>Economy ergonomics</td>
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<tr>
<td>Generation of exterior or interior finish</td>
<td>Automatic layout of exterior or interior trim panels according to the specified parameters</td>
<td>Aesthetic appeal</td>
</tr>
<tr>
<td>Interior furnishing</td>
<td>Automatic placement of furniture items in rooms according to the specified parameters</td>
<td>Design speed</td>
</tr>
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### 4 Discussion

The formulation of generative design tasks requires defining the purpose and limitations of the synthesis process of the design solution. For example, when synthesizing at the floor level, the task of generating apartment blocks of residential modules is proposed, taking into account the compactness of the building, which is reduced to minimizing the area of the outer shell. The geometric parameters of residential modules, the number of apartments, and the geometric parameters of apartment premises can be used as parameters in this task. As restrictions, the parameters of the number of variants of residential modules, functional connections of modules and premises, maximum standard sizes of modules, norms of apartment areas, normative minimum areas of apartment premises are considered.

At the levels of sections and the entire building, the geometric characteristics of the entire building are determined (shape on plan, composition of sections, number of floors), therefore, as an optimization problem, the task of finding the optimal location of the building on the construction site for optimal indoor insolation, taking into account the surrounding development, is solved. The parameters in this task are the number and configuration of sections of the building and their number of storeys. The limitations may be the parameters of the surrounding building, the geometric parameters of the construction site, the normative duration of the influence of solar radiation, the maximum number of floors of sections and the relationship of various sections. An information model with the best characteristics for construction conditions is synthesized and used in the future, including in the manufacture of structures.

The specification of modules, including all the necessary information about sizes, quantities and weights, are transmitted to the factory-made system from the information model using specialized means. This information is used by robotic machines and 3D printers to accurately recreate the digital model in physical form. After automatic manufacturing and assembly, the building modules are ready to be sent to the construction site.

In addition to achieving high efficiency parameters of the finished product, the digital production chain makes it possible to automate the design and manufacture of modular buildings as much as possible. With the introduction of artificial intelligence technologies, the digital production chain will be able to almost completely exclude a person from non-creative processes, especially in cases of repeated use of modules for the implementation of standard projects of modular buildings with different configurations of sections.
5 Conclusions

The study showed that the mass introduction of modular construction technologies in combination with the considered digital technologies plays an important role in solving the problems of achieving sustainable construction. The principles used in modular and prefabrication technologies show their advantage in comparison with traditional construction methods. Modular construction allows not only to solve the problems of housing affordability by providing citizens with economical and high-quality housing, but also to effectively solve the problems of environmental pollution.

Modern digital technologies can make an even greater contribution to the efficiency of construction. They improve the solution of the problem of increasing the efficiency of design solutions at the design stage, as well as the problem of ensuring environmental friendliness and accuracy of production. Robotic CNC machines and 3D printing make it possible to establish a well-established system of industrial manufacturing of modules, contributing to more efficient consumption of materials, and therefore reducing production waste. Generative technologies allow automating a significant part of the design process and provide tools for setting up a virtual pipeline for creating optimized design solutions according to the set goals and specified construction conditions.

The application of these technologies is based on a complex information model of a modular building that stores the necessary information about all elements of the project. This information is directly used in the production, construction, operation and processing of a modular building.

Integration of the design and production processes of a modular building into a continuous digital production chain will increase the sustainability of construction.

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