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PARAMETRIC DESIGN AND BIM FOR ADAPTIVE RAPID DEPLOYMENT SHELTERS CONSIDERING MULTI-CRITERIA OPTIMIZATION

Hrechka Uliana Mykhailivna
Master's Degree (Field of Study – Architecture and Construction, Programme Subject Area – Architecture and Town Planning), Project Architect, Contour Companies, 40950 Woodward Ave #300, Bloomfield Hills, MI 48304, USA, e-mail: uliana.hrechka@gmail.com, orcid: 0009-0008-8404-6538

Abstract. The relevance of this study is determined by the growing need for rapid infrastructure recovery, the deployment of mobile shelters, and the development of resilient housing solutions under emergency conditions. In the post-war reconstruction phase of Ukraine, the implementation of digital technologies in the construction sector has gained particular importance, as it enhances adaptability, energy efficiency, and resource optimization. Contemporary challenges demand a transition from static architectural design to parametrically controlled and analytically justified models capable of ensuring integrated lifecycle management of shelters.

***The aim of this article** is to develop a scientifically grounded concept for the use of parametric design and Building Information Modeling (BIM) technologies to create adaptive rapid deployment shelters that consider the multi-criteria optimization of structural, energy, and functional parameters.*

***The research methodology** is based on a systems approach that integrates methods of parametric modeling, multi-criteria optimization, BIM, and building lifecycle management. The study employs the principles of the Common Data Environment (CDE) and analytical comparison of design alternatives based on energy efficiency, mobility, cost, and environmental sustainability. The synthesis is based on the analysis of international and Ukrainian pilot projects, including RE:Ukraine Housing.*

***The results** show that integrating parametric design with BIM technologies provides an effective synergy between geometric modeling, techno-economic analysis, and operational analytics. It has been demonstrated that such integration allows the development of digital shelter models capable of automatically adapting to climatic, logistical, and resource constraints. The main implementation challenges identified include technical incompatibility of software environments, the regulatory uncertainty regarding the legal status of digital models, and the shortage of qualified specialists.*

***The scientific novelty** lies in developing a comprehensive concept for digital lifecycle management of adaptive shelters based on the integration of parametric modeling, multi-criteria optimization, and the BIM approach. For the first time, the structure of an integrated CDE for mobile structures has been substantiated, enabling interoperability among architectural, engineering, logistical, and analytical subsystems.*

***The practical significance** of the research lies in the possibility of using the obtained results to establish an effective digital management system for the design, deployment, and operation of shelters. The proposed solutions can be integrated into national reconstruction programs, digital construction standards compliant with ISO 19650, as well as international humanitarian initiatives for modular housing.*

Keywords: adaptive structures, digital management, multi-criteria optimization, energy efficiency, mobile structures.

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INTRODUCTION

Contemporary challenges associated with war, climate-related disasters, and the increasing frequency of humanitarian crises have created an urgent need for the development of rapidly deployable adaptive shelters capable of providing safe conditions for habitation, medical care, or logistical accommodation during emergencies. Traditional design approaches to such structures have proven inefficient due to the limited flexibility of structural solutions, high material intensity, and significant dependence on the human factor during assembly.

At the same time, the advancement of parametric design and Building Information Modeling (BIM) technologies offers new opportunities for integrating engineering, architectural, and logistical aspects within a unified digital platform. The application of multi-criteria optimization makes it possible not only to reduce the time required for shelter deployment but also to achieve a rational balance between strength, energy efficiency, mobility, and cost.

The scientific significance of this problem lies in the need to develop a comprehensive methodology for parametric modeling that ensures the adaptability of structures to various usage scenarios and environmental conditions. The practical value of the research is determined by the potential to design digital prototypes of next-generation shelters that combine the principles of sustainable architecture, automated production, and digital lifecycle management of the structure.

ANALYSIS OF PREVIOUS RESEARCH

The analysis of current research indicates the emergence of four interrelated scientific directions. The first focuses on the integration of BIM technologies with systems of sustainable and humanitarian construction. M. M. Gladdys et al. [7] propose a multi-level strategy for improving humanitarian construction by combining BIM with climatic analysis, which enables the adaptation of shelters to local environmental conditions. A. O. Bankole et al. [2] present a conceptual framework for applying artificial intelligence to enhance parametric design and 3D printing of architectural components, thereby improving automation and construction accuracy.

A. Mehdizade et al. [14] developed a post-disaster housing model in which parametric design is integrated with 3D printing technology to create flexible modules that can be rapidly manufactured and assembled. Future studies in this field should focus on integrating BIM, artificial intelligence, and 3D printing to develop a unified digital ecosystem for humanitarian construction.

The second direction concerns the use of parametric design to enhance the energy efficiency and thermal stability of shelters. A. Eltaweel et al. [6] conducted a parametric thermal analysis of temporary refugee shelters using an incremental approach and locally available materials, which made it possible to determine optimal configurations for various climatic conditions. K. Ajtayné Károlyfi and J. Szép [5] developed a parametric BIM model for assessing the embodied environmental impact during the conceptual design phase, enabling the integration of sustainability criteria at the early stages of construction. N. Mowafy et al. [15] created a BIM-based life cycle assessment system that optimizes the environmental and energy performance of buildings. Further research in this area should focus on developing unified digital protocols for the automated comparison of the environmental efficiency of shelters with different materials and geometries.

The third direction concerns parametric methods for optimizing the structure and typology of shelters for various emergency scenarios. R. K. Kunwar and S. Chander [12] demonstrated the potential of parametric design as a tool for large-scale housing construction capable of reducing both the duration and cost of the building process. Y. H. Kim et al. [11] applied BIM to model evacuation processes in subway shelters, proposing a methodology for reinforcing load-bearing elements and improving functional zoning. L. P. Da Mata et al. [13] examined the effectiveness of natural ventilation in container shelters through BIM-BES integration, which enabled the identification of optimal cooling solutions. Future research in this area should focus on modeling user behavior within shelters and combining parametric algorithms with ergonomic indicators to enhance safety and comfort.

The fourth direction focuses on improving the structural efficiency, material sustainability, and spatial optimization of shelters. B. B. Da Costa et al. [4] conducted computer simulations to evaluate the use of thermal insulation materials in temporary shelters in tropical countries, identifying the most energy-efficient combinations. V. Beatini et al. [3] established the minimum structural requirements for shelters designed for various types of emergency situations, forming the basis for standardizing parametric models. R. Karimi et al. [10] developed architectural design criteria for shelters based on the principles of the circular economy and reusability, contributing to the creation of sustainable structures. Further research in this area should focus on developing a digital lifecycle management system for shelters using parametric models, BIM, and artificial intelligence to predict technical conditions and facilitate the reuse of structural components.

Despite significant progress in the field of parametric design and BIM technologies, several issues remain unresolved, including the integration of parametric models with multi-criteria optimization systems, the assessment of shelter lifecycle performance, and the harmonization of digital standards for mobile structures. Methods that combine analytical, energy, and environmental parameters within a unified information environment remain insufficiently developed, while existing regulatory frameworks do not adequately account for the specific characteristics of digital modeling for temporary structures.

This study aims to address these gaps by developing an integrated methodology that combines parametric modeling, BIM, and multi-criteria optimization within a Common Data Environment (CDE). Such an approach ensures a new level of coherence among design, technological, and operational solutions, providing a foundation for digital reconstruction and enhancing the efficiency of adaptive shelters.

PURPOSE

The purpose of this article is to develop a scientifically grounded concept for the application of parametric design and Building Information Modeling (BIM) technologies to create adaptive rapid deployment shelters, taking into account the multi-criteria optimization of structural, energy, and functional parameters.

To achieve this purpose, the following objectives have been defined:

1. To analyze contemporary approaches to parametric design and BIM technologies in the field of prefabricated structures.
2. To substantiate the principles of integrating parametric modeling with multi-criteria optimization to enhance the efficiency of adaptive structures.
3. To develop recommendations for improving digital lifecycle management of shelters based on BIM and parametric technologies.

RESULTS AND DISCUSSION

Parametric design and BIM technologies represent the modern methodological foundation of digital transformation in the field of architectural and construction design, enabling the integration of geometric, structural, energy, and logistical parameters of an object into a unified model. In the context of prefabricated structures, these approaches make it possible to achieve a high level of structural adaptability, automate modeling processes, and optimize design solutions according to changing usage conditions.

Parametric models allow for the creation of variable architectural and structural systems in which the modification of individual parameters automatically recalculates the entire model. This is particularly important for rapid deployment shelters that must quickly adapt to diverse spatial, climatic, and functional scenarios. BIM, in turn, provides comprehensive visualization, simulation of the structure's lifecycle, and coordination among all participants in the design process, from architects to assembly teams (Table 1).

The interaction between parametric design and BIM demonstrates a systemic effect that combines algorithmic flexibility with informational precision. Parametric tools such as Grasshopper and Dynamo enable the generation of multiple structural design options based on variable parameters, including module dimensions, roof slope angles, material types, or load conditions [9]. This allows designers, even at the conceptual modeling stage, to evaluate which configuration provides the optimal

Table 1.

Comparative Characteristics of Parametric Design and BIM in the Context of Prefabricated Structures

Comparison Criterion	Parametric Design	BIM Technologies
Primary Function	Generation of variable forms and structures based on mathematical dependencies	Integrated management of all stages of an object's lifecycle
Type of Data	Geometric and logical parameters, algorithmic relationships	Information objects with attributes related to materials, cost, time, and energy efficiency
Level of Automation	High during form generation	High in coordination, visualization, and management processes
Flexibility of Modifications	Instant model updates when a parameter is changed	Systematic synchronization of data among interconnected models
Application in Prefabricated Structures	Optimization of structural geometry for mobility and stability	Planning, coordination, assembly, and maintenance of shelters

Source: Author's development based on [1; 7; 12, p. 474–476; 14; 15].

balance between mobility, energy efficiency, and structural stability.

Subsequent integration with BIM platforms such as Revit or ArchiCAD enables the automatic transfer of parametric data into a comprehensive digital model that includes a full set of attributes, ranging from material quantities and assembly time to cost and operational performance. The scientific and practical significance of this approach lies in its ability to create digital twins of shelters that not only represent the geometry of the structure but also simulate its behavior under different environmental conditions, such as temperature, wind, or seismic activity.

For example, in the development of modular medical units or temporary humanitarian aid centers in EU countries, parametric algorithms are used to adapt structural forms to the terrain, while BIM synchronizes logistical data during transportation and assembly. In the Ukrainian context, this approach is particularly relevant for constructing rapid deployment shelters in frontline and de-occupied areas, where the use of parametric-BIM modeling can reduce construction time by 30–40 percent, minimize design errors, and improve resource efficiency [14].

Thus, the combination of parametric design and BIM forms the foundation of a new paradigm in digital architecture focused on sustainability, adaptability, and the accelerated restoration of critical infrastructure.

The integration of parametric models and multi-criteria optimization within the BIM environment establishes a conceptual framework for developing intelligent architectural and engineering systems in which each parameter is logically connected to the project's objectives. This approach is not merely about automating form generation but about constructing a system of interrelated criteria, where the modification of a single variable (for example, material thickness or module inclination angle) simultaneously affects energy consumption, cost, and structural mobility (Table 2).

The principles of integrating parametric models and multi-criteria optimization within the BIM environment ensure not only the automation of the design process but, above all, the creation of a unified cognitive decision-making platform in which technical, economic, and environmental criteria are viewed as interrelated elements of a single system. Through this structure, BIM ceases to function merely as a tool for geometric modeling and becomes an analytical core capable of combining parametric data with information on resources, logistics, material sustainability, and operational scenarios.

The scientific novelty of this integrative approach lies in the fact that optimization algorithms do not simply calculate the efficiency of individual solutions but also manage the interaction among parameters of different types, for example, adjusting material thickness according to energy loss or suggesting changes in module configuration based on load forecasts and transport availability. In practical projects, this approach enables the creation of digital models that function as dynamic equilibrium systems, continuously coordinating the requirements of architects, engineers, logisticians, and environmental specialists [4].

In Ukraine's pilot digital construction initiatives, this integration principle is applied to coordinate decisions among participants in community reconstruction: the architectural team develops the parametric foundation, the engineering team incorporates criteria for structural strength and energy efficiency, and

Table 2.

Principles of Integrating Parametric Models and Multi-Criteria Optimization within the BIM Environment

Integration Principle	Essence of the Principle	Practical Significance
Systemic Interdependence of Parameters	Establishing logical connections among geometry, loads, materials, and functional requirements	Ensures a balance between structural stability, assembly speed, and energy efficiency
Iterative Optimization	Repeated testing of solutions with adjustment of criterion weighting coefficients	Enables identification of the optimal combination of characteristics without human intervention
Multi-Criteria Decision-Making	Simultaneous evaluation of technical, economic, environmental, and operational indicators	Increases the accuracy of selecting structural and technological options
Information Feedback	Transfer of optimization results into the BIM model for visualization, cost estimation, and simulation	Forms the foundation for digital lifecycle management of the structure
Contextual Adaptation	Automatic adjustment of design solutions according to external conditions (climate, terrain, resource availability)	Enhances the adaptability of shelters to different operational environments

Source: Author's development based on [1; 2, p. 105–106; 6; 7; 13, p. 16–33; 14].

local authorities add BIM data on cost, supply, and installation time [16].

As a result, a unified optimization ecosystem is formed in which any change in a parameter, even the price or delivery route, is automatically reflected in the final configuration of the shelter. This interaction mechanism creates the foundation for intelligent management of architectural and construction processes under conditions of uncertainty, which represents a key advantage of the integrated parametric-optimization approach.

Modern methods of applying BIM technologies and parametric modeling in the design of adaptive shelters are based on the principles of an integrated lifecycle, where each stage, from concept to operation, is represented within a digital ecosystem. These methods not only make it possible to create geometrically complex and functionally flexible forms but also provide measurable optimization of mobility, energy efficiency, and environmental sustainability. BIM serves as the fundamental environment in which parametric models function not as isolated engineering objects but as information-linked systems that account for material, temporal, energy, and logistical constraints.

As a result, the design process acquires an analytical nature in which every decision undergoes simulation, prediction, and automated consequence analysis (Table 3).

The use of Lifecycle BIM makes it possible to create a complete digital model of a shelter, from the design stage to dismantling. In international pilot projects involving modular medical facilities of this type, the implementation of the parametric-BIM approach reduced installation time by 28 percent and lowered logistics costs through module weight optimization [18]. The integration of energy-based BIM modeling with parametric algorithms allows the creation of shelters that automatically adjust their form and materials to the climatic conditions of a specific location.

In studies focused on prefabricated emergency hospitals, this combination of technologies reduced the energy consumption of heating and ventilation systems by 20–25 percent by optimizing module orientation and thermal insulation parameters [5]. Lifecycle Assessment (LCA) in this context enables forecasting of the carbon footprint of structures and the selection of materials with the lowest environmental impact.

In Ukraine, these methods have been implemented in the pilot project RE:Ukraine Housing, developed by the architectural firm Balbek Bureau, which became the first example of applying a digital design approach to modular housing complexes for internally displaced persons. Within this project, a BIM model of a residential section for 15 families in the Bucha district of Kyiv region was created, allowing simulation of structural, energy, and logistical scenarios for assembly, transportation, and subsequent disassembly [16].

Through parametric modeling, architects were able to optimize the geometry of modules for rapid assembly and improved thermal performance, while the use of the information model made it possible to automatically calculate material quantities and forecast operational costs. Thus, the Ukrainian pilot project confirmed that the combination of BIM and the parametric approach can serve as an effective tool not only for technical design but also for implementing digital reconstruction policies in the field of humanitarian housing.

Table 3.

Methods of Applying BIM Technologies and Parametric Modeling for the Creation of Adaptive Shelters

Method	Essence	Role in Ensuring Mobility, Energy Efficiency, and Sustainability
Lifecycle BIM	Development of a digital model of the structure considering operational, maintenance, and deconstruction stages	Provides forecasts of energy, resource, and time expenditures at each stage of the shelter's lifecycle
Generative Design	Use of algorithmic scenarios for the automatic generation of architectural and engineering solutions	Optimizes form, materials, and layout for rapid transportation and assembly
Energy Simulation	Integration of data on heat exchange, solar exposure, and ventilation into the digital model	Increases structural energy efficiency through the selection of optimal orientations and materials
Life Cycle Assessment	Evaluation of carbon footprint, energy consumption, and material reuse potential	Contributes to reducing environmental impact and promotes the principles of sustainable or "green" construction
Digital Twin & IoT	Integration of sensors and monitoring devices to track the structure's condition in real time	Allows adaptive management of heating, ventilation, and lighting systems based on actual operating conditions

Source: Author's development based on [6; 7; 13, p. 20–21; 14; 15].

The implementation of parametric and BIM approaches in the design of mobile structures is accompanied by a set of technical, regulatory, and organizational challenges that significantly reduce the efficiency of digital transformation in the construction sector. At the technical level, key barriers include limited compatibility among software environments, the absence of unified data formats for transferring parametric models into BIM platforms, and a shortage of high-performance computing resources for real-time multi-criteria simulations. A large number of architectural and engineering firms continue to work with isolated files, which prevents full integration of parametric algorithms into a shared design environment [4].

Regulatory barriers are associated with the lack of official standards and regulations in Ukraine governing the use of BIM technologies and parametric modeling for temporary or mobile structures. The current regulatory framework (DBN and DSTU) does not include provisions for digital modeling formats, data structures, model version control rules, or procedures for expert validation [4].

The absence of a legal definition for the status of an information model creates uncertainty regarding copyright, liability for errors in digital projects, and the procedures for transferring models between contractors. In addition, the requirements for energy efficiency and environmental certification of shelters are not yet adapted to prefabricated structures, which complicates the registration and approval of such projects at the state level.

Organizational challenges include insufficient digital competence among specialists, the fragmented implementation of BIM in the public sector, and the lack of centralized platforms for interagency coordination. Most Ukrainian communities do not have professionals capable of working with parametric scenarios or interpreting data from BIM models for decision-making. There is also no system for certifying BIM users, which prevents the establishment of quality control over digital models.

An additional challenge is the gap between architectural firms that possess modern digital tools and clients from the state or municipal sector who lack the necessary technical infrastructure to receive or store digital models [2, p. 104]. At the international level, another issue is the inconsistency between Ukrainian practices and the requirements of ISO 19650 [18] concerning information environment management. This discrepancy complicates the integration of Ukrainian pilot projects into international digital supply chains and limits opportunities for attracting foreign investment.

Therefore, the effective implementation of parametric and BIM approaches in the field of mobile structures requires not only technological modernization but also comprehensive data standardization, regulatory framework updates, and professional training to ensure continuous management of the digital lifecycle of buildings.

Improving the system of digital lifecycle management for adaptive shelters should be achieved through the combination of controlled parameterization, standardized data exchange, and embedded decision-making analytics. At the data level, the foundation should be a Common Data Environment with version control, role management, and change tracking, built on open Building Information Modeling (openBIM) formats, including Industry Foundation Classes (IFC 4.3) and BIM Collaboration Format.

For each stage of the lifecycle, from concept to deconstruction, client information requirements should be defined to formalize the set of model attributes and parameters. Parametric element libraries should be standardized as "solution catalogs" with predefined variable ranges and limit state checks, preventing invalid configurations at the generation stage. Design choices should be made through multi-criteria procedures with transparent weighting coefficients and automated generation of Pareto sets.

The system of criteria must include indicators such as deployment time, logistical complexity, specific cost, operational energy consumption, and carbon footprint, with LCA integration into the BIM model according to the European standard EN 15978. During the operational phase, it is advisable to apply DT technologies integrated with IoT sensor devices and deviation detection algorithms.

This approach makes it possible to synchronize actual parameters of the microclimate, loads, and material degradation with maintenance plans, automatically updating design assumptions. Data quality is maintained through a formalized Quality Assurance/Quality Control (QA/QC) framework that provides automatic verification of information requirements, clash detection, and energy balance validation before each stage of model "freezing," as well as decision-tracking audits to ensure the reproducibility of results.

From an organizational standpoint, the system should be based on a content management model for BIM and parametric scenarios, with clearly defined roles for the CDE administrator, discipline coordinators, and data analytics specialists. To support this framework, BIM Execution Plans (BEP) and contractual conditions for data providers are developed to ensure consistency and repeatability of processes.

At the regulatory level, it is necessary to harmonize Ukrainian requirements with the international standard ISO 19650 [9], which defines information management practices throughout the lifecycle of buildings and structures.

It is also advisable to introduce simplified approval procedures for temporary structures when a complete certified information model is available. The effectiveness of implementation should be evaluated using a system of KPI, including reductions in deployment time, coordination errors, specific energy consumption, and lifecycle cost. Establishing such KPIs in pilot projects will ensure the scientifically grounded adaptation of digital technologies to the realities of Ukraine and improve the effectiveness of lifecycle management for adaptive shelters.

CONCLUSIONS

The study has demonstrated that the integration of parametric design and BIM technologies enables the development of adaptive, energy-efficient, and sustainable shelters based on integrated digital lifecycle management. It has been established that the synergy between parametric models and multi-criteria optimization provides a foundation for intelligent forecasting of technical and operational solutions.

The key implementation challenges identified include the technical incompatibility of software platforms, the lack of regulatory clarity for digital models, fragmented management procedures, and low digital competence among project participants. It is proposed to improve the system of digital lifecycle management for shelters through the use of a Common Data Environment, standardized client requirements, and open formats such as IFC 4.3. The integration of LCA and DT methods enhances monitoring efficiency and predictive management capabilities.

Further research should focus on developing national digital construction standards in accordance with ISO 19650 and advancing Ukrainian pilot projects such as RE:Ukraine Housing through the use of artificial intelligence for automated optimization of parametric solutions.

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АНОТАЦІЯ

Гречка Уляна. Параметричне проєктування та BIM для адаптивних притулків швидкого розгортання з урахуванням багатокритеріальної оптимізації

Актуальність дослідження зумовлена зростанням потреби у швидкому відновленні інфраструктури, розгортанні мобільних укриттів та формуванні стійких житлових рішень у надзвичайних умовах. В умовах післявоєнного відбудовного циклу України особливої ваги набуває впровадження цифрових технологій у будівництві, які забезпечують підвищення адаптивності, енергоефективності та оптимізацію використання ресурсів. Сучасні виклики вимагають переходу від статичного архітектурного проєктування до параметрично керованих і аналітично обґрунтованих моделей, здатних забезпечити інтегроване управління життєвим циклом притулків.

***Мета статті** полягає в розробленні науково обґрунтованої концепції використання параметричного проєктування та технологій BIM для створення адаптивних притулків швидкого розгортання з урахуванням багатокритеріальної оптимізації конструктивних, енергетичних і функціональних параметрів.*

***Методологія дослідження** базується на системному підході та поєднує методи параметричного моделювання, багатокритеріальної оптимізації, BIM і життєвого циклу споруди. Використано принципи середовища загальних даних (CDE), аналітичного порівняння варіантів конструкцій за критеріями енергоефективності, мобільності, вартості та екологічної стійкості. Узагальнення проведено на основі аналізу міжнародних і українських пілотних проєктів, зокрема RE: Ukraine Housing.*

***Результати дослідження** показали, що інтеграція параметричного проєктування та технологій BIM забезпечує ефективну синергію між геометричним моделюванням, техніко-економічним аналізом та експлуатаційною аналітикою. Доведено, що така інтеграція дає змогу формувати цифрові моделі притулків, здатні автоматично адаптуватися до кліматичних, логістичних і ресурсних обмежень. Виявлено основні проблеми впровадження – технічну несумісність програмних середовищ, нормативну неврегульованість статусу цифрової моделі та недостатню підготовку фахівців.*

***Наукова новизна** полягає у формуванні цілісної концепції цифрового управління життєвим циклом адаптивних притулків на основі поєднання параметричного моделювання, багатокритеріальної оптимізації та BIM-підходу. Вперше обґрунтовано структуру інтегрованого середовища даних CDE для мобільних споруд, що дозволяє забезпечити взаємодію між архітектурними, інженерними, логістичними й аналітичними підсистемами.*

***Практична значущість** полягає в можливості використання отриманих результатів для створення ефективної системи цифрового управління процесами проєктування, розгортання та експлуатації притулків. Запропоновані рішення можуть бути інтегровані в державні програми відбудови, у стандарти цифрового будівництва відповідно до ISO 19650, а також у міжнародні гуманітарні ініціативи зі створення модульного житла.*

Ключові слова: *адаптивні конструкції, цифрове управління, багатокритеріальна оптимізація, енергоефективність, мобільні споруди.*

АВТОРСЬКА ДОВІДКА:

Гречка Уляна, магістр (галузь знань – Архітектура та будівництво, спеціальність – Архітектура та містобудування), Проєктна архітекторка, Contour Companies, 40950 Woodward Ave #300, Bloomfield Hills, MI 48304, USA, e-mail: uliana.hrechka@gmail.com, orcid: 0009-0008-8404-6538.

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