RESOURCE-SAVING TECHNOLOGIES AND STRUCTURAL OPTIMIZATION OF CIVIL DEFENSE PROTECTIVE STRUCTURES

Valery Usenko[1]
Anton Hasenko[2]
Dmytro Usenko[3]

DOI: https://doi.org/10.30525/978-9934-26-531-0-3

This study thoroughly examines modern approaches to the restoration and optimization of civil defense protective structures, which have become increasingly relevant amid growing threats, limited resources, and the need for rapid responses to critical situations. The reliability of such structures is determined not only by their strength but also by their ability to withstand combined loads, including seismic, dynamic, and vibrational impacts, as well as by the durability of the materials used in construction and reconstruction. In this context, modern construction trends necessitate the expansion of methodological tools and the adoption of innovative technologies, such as 3D printing, eco-friendly materials, and probabilistic risk assessment models, to enhance the efficiency of designing and operating protective structures. *The subject* of the study involves analyzing methods for restoring damaged buildings, evaluating their operational suitability, including under man-made loads, such as those experienced during military actions, and developing approaches for predicting service life under such conditions while optimizing reconstruction costs. Traditional methods for enhancing structural load-bearing capacity, such as applying additional layers of reinforced concrete, remain important but may be limited in efficiency due to modern demands for construction speed and structural

---

[1] Doctor of Technical Sciences,
Professor at the Department of Building and Civil Engineering,
National University "Yuri Kondratyuk Poltava Polytechnic", Ukraine
[2] Doctor of Technical Sciences,
Professor at the Department of Highways, Geodesy, Land and Management,
National University "Yuri Kondratyuk Poltava Polytechnic", Ukraine
[3] Ph.D. of Building and Civil Engeneering, MPhys,
Associate Professor of the Department of Chemistry and Physics,
National University "Yuri Kondratyuk Poltava Polytechnic", Ukraine

adaptability. Meanwhile, the adoption of additive technologies, enabling the rapid construction of complex structures, opens new perspectives for the design and construction of protective facilities. *The research methodology* is based on an integrated approach that includes classical experimental testing methods, numerical modeling of stress-strain states, and probabilistic risk models. The use of probabilistic limit state design models allows for the consideration of uncertainties in material properties and loads, while the implementation of automated monitoring systems enhances safety and enables rapid responses to potential damage. The incorporation of eco-friendly materials plays a crucial role, not only improving structural durability but also ensuring economic and environmental efficiency. *The objective of the study* is to develop scientifically grounded methods for evaluating structural conditions, predicting service life, and optimizing the construction and reconstruction of civil defense protective structures. The utilization of advanced technologies, such as 3D printing and composite materials, can significantly enhance construction efficiency while reducing overall restoration costs. An essential aspect of the study involves considering economic feasibility and resource conservation, which enables more efficient use of available construction materials and minimizes waste. *The study concludes* that the integration of modern technologies significantly improves the quality and efficiency of restoring damaged structures, particularly through the use of resource management optimization models and structural durability prediction methods. The analysis demonstrated that the application of additive technologies, eco-friendly materials, and probabilistic risk assessment methods results in significant time and resource savings, which are critically important for civil defense facilities. Thus, this study contributes to the advancement of modern construction and civil defense engineering by offering comprehensive methods for assessing and predicting the technical condition of structures. Practical recommendations regarding material selection, the application of modern design methods, and risk management strategies significantly enhance the safety and durability of strategically important infrastructure. Future research in this field could focus on refining structural condition assessment algorithms, developing adaptive risk management models, and integrating artificial intelligence for monitoring and automated design of protective structures.

1. Introduction

The development of modern construction and restoration technologies for damaged structures faces increasing challenges amid global socio-economic and environmental changes. In particular, ensuring the reliability of building structures during emergencies caused by military conflicts, natural disasters, and technological accidents has become increasingly relevant. Under such conditions, resource-efficient technologies play a crucial role in accelerating the restoration process, alongside the effective design of civil defense protective structures to safeguard the population and critical infrastructure [5, p. 45; 16, p. 152].

Addressing these challenges is feasible only through the integration of innovative approaches to the design, construction, and restoration of structures. In this context, particular attention should be given to technologies such as additive manufacturing (3D printing), the use of self-compacting concrete with recycled components, and the implementation of a systematic approach to organizing protective structures. It is also essential to consider material and technology standardization, as well as ensuring interlayer adhesion in structures created through layered construction. Scientific research in this field highlights the need for further development of comprehensive methods for assessing the durability, reliability, and economic feasibility of innovative structural solutions.

The primary scientific challenges addressed in this study encompass several key aspects:

Ensuring the reliability of civil defense protective structures. Modern realities necessitate improving the protective properties of structures while considering external factors, such as blast waves, shelling, and seismic shocks. It is crucial to identify optimal materials and structural solutions to enhance resilience against these loads [3, p. 18; 16, p. 155].

Optimizing the restoration of damaged structures using resource-efficient technologies. The adoption of renewable materials and cost-effective technologies, such as 3D printing and polymer recycling, significantly reduces the time and resources required for restoration work.

Integration of civil defense engineering measures. Enhancing safety requires the development of unified standards for the design and operation of protective structures. It is essential to incorporate international experience while adapting it to local conditions to establish an effective system for population protection [7, p. 22; 11, p. 35].

The primary objective of this research is to develop a comprehensive approach to designing and implementing technologies for constructing and reconstructing civil defense protective structures under emergency conditions. This approach aims to combine high structural reliability with improved energy efficiency, environmental sustainability, and cost-effectiveness.

The objectives of this study include:

– Investigating modern technologies for constructing protective structures and their adaptation to real-world operating conditions;

– Analyzing the properties of innovative materials, particularly concrete with recycled aggregates and repurposed polymers, to enhance structural resilience against extreme impacts;

– Developing variational methods for strength calculations of complexly loaded structures under combined loads;

– Evaluating the efficiency of potential 3D printing implementation to reduce construction or reconstruction time and costs;

– Formulating recommendations for organizing civil defense systems and implementing safety measures at the design and construction stages.

The relevance of this study is driven by the need to implement innovative technologies that address contemporary challenges. The findings of this work can form the foundation for developing new standards for designing protective and restorative structures, contribute to reducing the environmental impact of construction activities, and ensure a high level of population safety during emergencies.

2. Comprehensive Methods for Structural Strength Analysis in Civil Defense Systems Using Resource-Efficient Technologies

Comprehensive structural strength analysis is a critically important stage in the design and restoration of civil defense protective structures. Under extreme loading conditions, such as seismic shocks, blast waves, or bombardments, the need arises for modern methods to assess strength and reliability. The integration of resource-efficient technologies into this process not only enhances structural resilience but also optimizes resource and time expenditures for construction and restoration [16, p. 150; 19, p. 1285].

The Significance of Strength and Reliability in Civil Defense Systems

The strength and reliability of protective structures are key indicators of their effectiveness in preserving lives and public health during emergencies. These structures must ensure safety even under simultaneous exposure to multiple types of loads, necessitating detailed modeling of critical scenarios. According to international experience, it is essential to consider the behavior of materials and structures under dynamic conditions [3, p. 20; 16, p. 153].

Modern protective structures are designed with factors such as operational lifespan, resistance to repetitive loads, and self-healing capabilities after damage. For example, in some countries, shape-memory materials are actively used, enabling partial restoration of properties after deformation.

Methods for Structural Strength Assessment Under Combined Loads

To evaluate the behavior of structures in complex conditions, the variational method of plasticity theory is used to determine their ultimate states [19, p. 1288]. This method accounts for the simultaneous influence of vertical and horizontal loads, which frequently occur during earthquakes or explosions. Additionally, numerical methods, such as the finite element method, play a significant role in developing detailed structural models and analyzing their response to external factors [21, p. 195; 24, p. 310].

Stochastic modeling allows for variability in material properties and load effects. Specifically, numerical Monte Carlo methods facilitate the assessment of critical scenario probabilities and the identification of the most vulnerable structural elements [23, p. 12; 24, p. 315].

The Use of Additive Technologies in Structural Reinforcement and Restoration

Additive technologies, particularly 3D printing, open new possibilities for the rapid restoration and reinforcement of damaged structures. This method enables the creation of complex architectural forms with minimal material waste. One of the key advantages of 3D printing is the ability to use eco-friendly materials, such as recycled plastics or bio-based composites [2, p. 215; 8, p. 490].

A primary challenge remains the standardization of material properties for additive manufacturing. Ensuring adhesion between concrete layers is especially critical, as it directly impacts the durability and strength of structures.

Innovative Materials for Civil Defense Structures

The use of self-compacting concrete with recycled components enhances the mechanical strength of structures. These materials exhibit high resistance to cracking and corrosion, making them suitable for facilities operating under extreme conditions [8, p. 495; 12, p. 101290; 10, p. 385].

Additionally, secondary materials such as polymers are employed for reinforcing structural elements. This approach reduces reliance on natural resources and improves the environmental sustainability of construction projects [12, p. 101292; 9, p. 220].

Assessment of Structural Reliability in Civil Defense Systems Probabilistic analysis methods play a crucial role in predicting structural longevity and safety. Fault tree analysis helps identify the most critical damage scenarios, while stochastic models account for unpredictable factors during structural operation [23, p. 13; 24, p. 318].

These methods are particularly important for protective structures, which must maintain high safety levels even under significant deviations in material properties and load conditions [3, p. 22; 23, p. 14; 16, p. 156].

Comprehensive Approaches to Cost and Time Optimization in Restoration Projects. Efficient management of restoration projects involves developing cost and time optimization models. Specifically, linear and resource-dependent scheduling models minimize project duration and reduce work interruptions [1, p. 65; 5, p. 52].

These approaches facilitate the creation of flexible schedules that account for potential delays in material supply and changes in site conditions. They improve productivity and lower overall restoration costs.

Thus, the application of comprehensive methods for assessing the strength and reliability of civil defense structures ensures effective protection of the population and infrastructure. The integration of modern technologies and materials contributes to cost and time optimization, which is essential for rapid emergency response. Further development of these methods will enhance the resilience and durability of protective structures.

3. Main Part

3.1. Experience in the Construction of Rapidly Assembled Civil Defense Structures in Ukraine

Protective structures are specialized buildings designed to shelter the population from weapons of mass destruction during special periods and emergencies in peacetime. According to DBN V.2.2-5:2023, protective structures are classified into shelters, radiation protection shelters, dual-purpose structures, and the simplest shelters. Temporary protective structures at urban transport stops fall under the category of the simplest shelters, referring to fortification structures that reduce harm to people from hazardous consequences during emergencies. The relevance of such temporary protective structures at public transport stops has increased significantly during the ongoing military actions in Ukraine.

The functional purposes of temporary protective structures at urban transport stops include:

– Protection of civilians from artillery shelling, air raids, and other military actions;

– Temporary shelter during air raid alerts;

– Ensuring passenger safety in critical situations.

Based on their structural type, temporary protective structures at urban transport stops are classified into:

– Reinforced modular metal shelters;

– Precast reinforced concrete rapid-assembly structures;

– Reinforced pavilions with additional protection.

The primary structural requirements for protective structures at urban transport stops include wall and ceiling thicknesses of no less than 20–25 cm, capable of withstanding collapses of lightweight structures; the presence of emergency exits, ventilation openings, and seating areas. Additional requirements include rapid installation (assembly), mobility, dismantling and relocation capabilities, and economic feasibility.

The placement of such temporary structures at urban transport stops is determined by population density, transport hub locations, and potential risk zones. It is essential to ensure maximum accessibility of shelters for various population groups, including people with disabilities. The experience of using temporary protective structures demonstrates their effectiveness as an element of civil defense during wartime, making them an essential component of population safety. *Figure 2* shows a mobile rapid-assembly shelter installed at urban transport stops in Dnipro.

Figure 1. Mobile shelter installed near the Nova Poshta logistics center in Poltava: a) exterior view; b) interior organization

Source: [16, p. 153]

At the same time, the requirements of DBN V.2.2-40:2018 establish general provisions for ensuring the accessibility of buildings and structures, including their reasonable adaptation to the needs of people with limited mobility. Ensuring the accessibility of public transport stops for people with limited mobility is an essential component of creating an inclusive urban environment. Architectural solutions outlined in the specified regulatory document promote a comprehensive approach to space arrangement.

Figure 2. Mobile rapid-assembly shelter installed at urban transport stops in Dnipro: a) exterior view; b) interior organization

Source: [16, p. 155]

Specifically, the installation of gently sloped ramps with reliable handrails and non-slip surfaces is necessary. These ramps allow wheelchair users and elderly individuals to move freely around the stop area. Comfortable waiting areas at stops should include weather shelters, ergonomic benches with supportive handrails, and resting spots. Additionally, as mentioned above, public transport waiting areas should incorporate temporary protective structures.

Legal regulations mandate strict adherence to state building codes and accessibility standards. Each architectural solution must aim to ensure equal rights and opportunities for all population groups. *Figure 3* shows the general view of a temporary protective structure at urban transport stops in Dnipro, featuring an accessibility element (a gently sloped ramp) for people with limited mobility. Informational signs and clear markings are displayed on the exterior walls of the protective structure.

Figure 3. General view of a temporary protective structure at urban transport stops in Dnipro with an accessibility element for people with limited mobility

Source: [16, p. 155]

3.2. Application of Modern Additive Technologies (3D Printing) in Construction

Modern additive technologies, particularly 3D printing, are becoming an essential tool in construction, especially for the rapid restoration of damaged structures and the creation of new protective facilities. This technology allows for the printing of structural elements with minimal material consumption, time, and labor, promoting resource-efficient construction [2, p. 218].

Key Stages of the 3D Printing Process

The additive construction process consists of several sequential stages that ensure precise printing of the structure while meeting engineering requirements.

Table 1

Main stages of the 3D printing process

Stage	Description	Basic parameters
Digital Model Creation	Design of the structure using CAD/BIM software to model geometry and parameters, considering load, shape, and functionality.	CAD model, geometric parameters, load analysis, design optimization.
Concrete Mix Preparation	Preparation of a special high-plasticity mix ensuring uniform layer deposition and proper curing.	Mix composition (cement, water, additives), flowability, curing rate.
Printing Process	Automated layer-by-layer printing, where a specialized printing system applies the mix according to the digital model, ensuring precise positioning and layer parameters.	Layer thickness (5–15 mm), feed rate, print head movement accuracy.
Curing and Quality Control	Solidification of the structure through natural or accelerated curing, followed by strength and performance testing.	Curing time, test results (compression, bending, etc.).

Source: [9, p. 218]

The first stage involves creating a digital model of the structure using specialized software, such as Building Information Modeling (BIM). This software enables engineers to model the geometry of the future structure while accounting for its design features and functional purpose. During this stage, parameters such as wall thickness, material strength, load capacity, and structural stability are determined [2, p. 208].

The second stage focuses on preparing the concrete mix for printing. The material must be highly plastic, fast-curing, and sufficiently strong to meet structural requirements. To achieve these properties, the concrete mix is modified with additives that enhance its rheological characteristics, ensuring even application and rapid curing without additional treatment. Besides standard concrete compositions, geopolymer-based materials and mixes containing recycled polymer additives can be used, further enhancing the environmental sustainability of the process [8, p. 492].

The third stage involves the printing process itself. Automated systems equipped with robotic manipulators or rail mechanisms ensure precise layer-by-layer material deposition. Software controls the movement of the print head, allowing concrete or polymer mixes to be applied according to the digital model. A critical parameter here is layer thickness, which affects the quality and durability of the final structure. Typically, the layer thickness ranges from 5 to 15 mm, ensuring optimal adhesion between layers and uniform material drying. The material feed rate is also controlled, typically ranging from 30 to 50 cm/h, depending on the structure's complexity and the material used [25, p. 25].

The final stage involves curing and quality control. Once printing is complete, the structure undergoes further inspection to verify compliance with design specifications. A crucial criterion is compressive strength, tested 24 to 48 hours after printing. Some structures may undergo additional treatment, such as applying protective coatings or waterproofing compounds to enhance durability [8, p. 494].

Material Characteristics for 3D Printing

The use of specialized materials is one of the key factors for the successful implementation of 3D printing. The primary material used is self-compacting concrete (SCC), known for its high flowability and rapid curing without the need for vibration [10, p. 387].

The main physical and mechanical properties of these materials include:

Compressive strength (σ_c) and flexural strength (σ_f), calculated using the following formulas:

$$\sigma_c = \frac{P}{A}, \quad \sigma_f = \frac{3PL}{2bd^2}, \tag{1}$$

Elastic modulus (E), determining the material's deformation properties:

$$E = \frac{\Delta\sigma}{\Delta\varepsilon}, \tag{2}$$

where $\Delta\sigma$ – represents stress change, and, $\Delta\varepsilon$ – represents strain change [25, p. 27].

Recycled polymers and other secondary components can be incorporated into 3D printing mixes, enhancing the material's environmental sustainability [12, p. 101295].

Advantages and Limitations of Additive Construction

The application of 3D printing in construction offers numerous advantages, including cost optimization, faster project completion, and improved structural quality.

One of the primary benefits is construction speed. Additive technologies can reduce construction timelines several times compared to traditional methods. The automated printing process eliminates the need for formwork preparation, which is essential in conventional construction. For example, printing a standard single-story shelter can take 24 to 48 hours, whereas a similar structure built traditionally would require at least 3 to 4 weeks [9, p. 222].

A second significant advantage is material savings. 3D printing minimizes material consumption through precise dosing and the absence of excess waste. Unlike traditional construction, where excess concrete often needs disposal, additive construction uses only the material required for each layer. This approach reduces material consumption by 30–50%, depending on the chosen printing technology [8, p. 496].

A third advantage is design flexibility. Since printing is based on digital models, it enables the creation of complex geometric shapes that are challenging to achieve using conventional methods. This not only enhances the aesthetic appeal of structures but also improves their load-bearing capacity through optimized designs, such as bionic forms or fractal geometries [23, p. 12].

Despite numerous advantages, additive construction also faces certain limitations. One of the most significant challenges is the need for material standardization. Currently, no unified international standards exist for mixture composition, strength testing methods, or interlayer adhesion parameters. This lack of standardization complicates the large-scale implementation of 3D printing, especially in civil and protective construction [2, p. 213].

Another technical challenge is interlayer adhesion. As the printing process occurs layer by layer, it is crucial to ensure strong bonding between layers to prevent microcracks and degradation of mechanical properties.

Table 2

Advantages and Limitations of Additive Construction

Category	Description	Advantage / Limitation
Construction Speed	Automation of the printing process significantly reduces construction time compared to traditional methods.	*Advantage:* Reduces construction time by 60–70% (e.g., shelters can be printed within 24–48 hours).
Material Savings	Precise mixture dosing in 3D printing minimizes material waste, commonly caused by formwork and over-pouring in traditional construction.	*Advantage:* Reduces material costs by 30–50%.
Design Flexibility	Enables the creation of complex geometric forms without the need for additional formwork or specialized tools.	*Advantage:* High customization and innovative design.
Material Standardization	The lack of unified international standards for concrete mixes and 3D printing parameters complicates the widespread adoption of the technology.	*Limitation:* Requires the development of unified standards and norms.
Interlayer Adhesion	Ensuring proper bonding between layers is critical for structural durability, but microcracks may form during the printing process.	*Limitation:* Requires further research to improve interlayer adhesion.
Height Limitations	Current 3D printing technologies are limited in terms of structure height, affecting the feasibility of multi-story construction.	*Limitation:* Applicable primarily for 2–3-story structures; requires integration with traditional methods.

Source: [9, p. 220]

Figure 4 presents an example of interlayer strength analysis for 3D-printed structures. Testing indicates that layer bonding can vary significantly depending on the mixture type and printing technology used. Poor adhesion between layers can lead to material delamination and loss of structural stability [10, p. 389].

Additionally, height limitations remain a concern. Most current 3D-printed structures do not exceed two to three stories due to the limited load-bearing capacity of printed materials. This means that multi-story construction may require a hybrid approach, combining additive technologies with traditional methods, complicating project execution [8, p. 496].

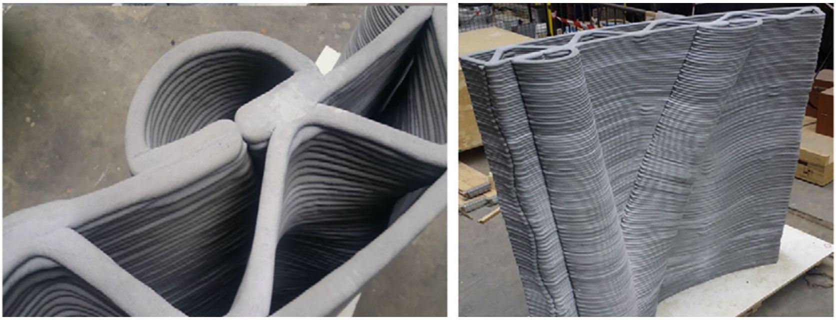

Figure 4. 3D-printed wall structure

Source: [9, p. 217]

Application of Additive Technologies in Protective Structures

In the context of civil defense systems, additive technologies are gaining popularity due to their ability to facilitate fast, efficient, and cost-effective construction of protective structures. 3D printing allows for the creation of shelters, bunkers, and walls that provide protection against blast waves and other hazardous impacts, often utilizing recycled materials to enhance environmental sustainability.

Through digital models developed with BIM technologies, it is possible to precisely reproduce all necessary structural parameters, ensuring high printing accuracy for each layer [25, p. 29]. *Figure 5* illustrates the printing of a modular shelter using secondary materials, which helps reduce costs and environmental impact.

A key example of additive technology application in civil defense systems is the construction of protective barriers in high-risk zones, where rapid project execution is crucial. Studies show that 3D printing can reduce construction time by 40% compared to traditional methods, enabling quick responses to emergencies and minimizing risks for the population [2, p. 220].

The additive approach facilitates the construction of complex geometries that are either impractical or economically unfeasible to achieve using traditional methods. Furthermore, structures can be printed directly on-site, within the emergency zone, allowing for swift restoration or creation of new protective facilities.

Figure 5. Construction of a shelter using 3D printing

Source: [2, p. 208]

To better understand the main aspects of the application of additive technologies in protective structures, the following table compares the key parameters of traditional restoration methods with the additive approach in the context of civil protection systems:

Table 3 highlights the primary advantages and limitations of additive technologies compared to traditional restoration methods in the context of civil defense systems [8, p. 498].

On one hand, 3D printing significantly reduces construction time, lowers material costs, and enhances design flexibility, which is particularly beneficial for protective structure restoration. On the other hand, challenges remain in material standardization and achieving high-quality interlayer adhesion, indicating the need for further research and technological advancements.

Thus, integrating additive technologies into civil defense systems not only reduces the resource intensity of construction but also improves the efficiency of restoration efforts, which is critically important under modern emergency conditions [2, p. 220].

Table 3

Comparison of Construction Methods for Civil Defense Structures

Parameter	Traditional Methods	Additive Technologies (3D Printing)	Analysis
Construction Time	Lengthy, averaging 100% of the baseline time.	Reduces to 60% of the baseline time.	Additive technology shortens construction time through automation and formwork elimination.
Material Costs	100% of material costs using traditional methods.	Reduces to 70–80% of baseline costs.	Precise material dosing minimizes waste and excess consumption.
Environmental Sustainability	Limited, due to the use of new natural resources.	Enhanced, through the use of recycled materials.	Recycled materials reduce CO_2 emissions and consumption of primary resources.
Design Flexibility	Limited by formwork shape and traditional techniques.	High – enables complex geometric designs.	3D printing allows for innovative designs without specialized tools.
Interlayer Adhesion	Achieved through additional measures but may be inconsistent.	Challenges with interlayer adhesion, requiring further technological advancements.	Poor layer bonding can reduce structural strength, necessitating parameter optimization.
Rapid Restoration	Limited, requiring dismantling and reconstruction.	High – structures can be printed directly on-site.	Rapid response is critical for civil defense systems, allowing for quick restoration of damaged facilities.

Source: [10, p. 389]

The economic efficiency of 3D printing in construction is defined by the technology's ability to reduce overall construction costs through material optimization, shorter project timelines, and automated production processes. One of the key indicators of efficiency is the reduction in material costs, averaging 30–50% compared to traditional construction methods [8, p. 497]. This is achieved through precise dosing of mixtures during 3D printing, ensuring that only the required amount of material is used for each structural layer.

In traditional construction, significant material waste occurs due to over-pouring, formwork installation, and other preparatory operations. In contrast, 3D printing employs digital control over material delivery, minimizing waste and reducing raw material costs. Furthermore, automation eliminates the need for a large workforce, positively affecting project economics.

Another critical factor is the reduction in construction time. Through automation and continuous large-scale printing, 3D technology enables much faster project completion than traditional methods. This means that construction investments yield returns more quickly, with the operational phase commencing earlier. For example, some projects demonstrate up to a 60% reduction in construction timelines compared to conventional methods, significantly enhancing the overall economic feasibility of the technology.

The ability to incorporate eco-friendly materials into the 3D printing process further enhances economic efficiency. Using recycled materials, such as repurposed plastics and industrial waste-based additives, not only optimizes costs but also promotes circular economy principles. This is especially relevant in modern conditions, where reducing environmental impact is a priority for the construction industry.

An additional economic advantage of 3D printing is the capability to create complex geometries that are challenging or economically impractical to achieve through traditional methods. Digital modeling allows for the design of structures optimized for structural characteristics, reducing weight and material consumption while maintaining high strength levels. This optimization lowers not only construction costs but also operational expenses, as lighter structures require fewer reinforcements and formwork during installation.

Economic efficiency is also evident in the reduced labor costs associated with 3D printing. Since the process is automated, the need for a large, skilled workforce is significantly diminished. This reduction impacts not only direct wages but also the costs associated with site management, logistics, and preparation. Moreover, lower occupational safety risks further enhance overall project cost-effectiveness.

The cost-effectiveness of 3D printing in construction is determined by numerous factors, including reduced material costs, reduced construction time, and optimized labor utilization. Thanks to automation and precise digital process control, 3D printing allows for significant cost reductions, which is especially relevant for civil protection projects, where speed of response and promptness of restoration of facilities are critical.

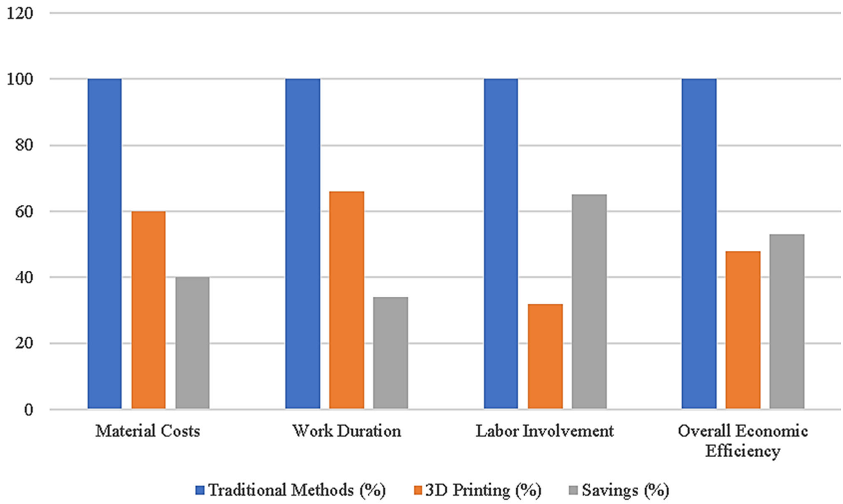

Figure 6. Comparison of cost-effectiveness of 3D printing and traditional construction

Source: [25, p. 27]

In traditional construction, material expenses form the primary budget component, with baseline costs set at 100%. 3D printing reduces material consumption by an average of 40% through precise dosing and minimal waste generation. This is achieved by eliminating the need for formwork, automating material application, and incorporating secondary raw materials [2, p. 221]. Consequently, the average material costs for 3D printing are approximately 60% of the traditional level.

The project duration for traditional construction involves extensive preparatory processes, such as formwork installation, concrete pouring, curing time, and formwork removal. These activities significantly extend project timelines. In contrast, 3D printing follows a continuous, automated process, reducing construction duration by approximately 35% [8, p. 489].

As a result, 3D printing projects typically require only 65% of the time needed for traditional construction.

Traditional construction also relies heavily on labor, requiring skilled and unskilled workers, engineering staff, and additional project management resources. In comparison, 3D printing automates most tasks, drastically reducing the need for manual labor. On average, labor cost savings amount to 65%, meaning 3D-printed projects require only 35% of the workforce needed for traditional methods [2, p. 223].

The comprehensive economic efficiency of 3D printing considers all aforementioned factors, including material costs, project duration, and labor savings. Based on average values, the overall cost savings amount to 52%. This indicates that 3D printing requires only 48% of the total expenses associated with traditional construction.

Economic models used for efficiency evaluation compare traditional construction costs with those of additive manufacturing. As noted in [25, p. 30], the implementation of 3D printing can reduce material expenses to 70% of the baseline level. Combined with shorter project timelines and reduced labor requirements, this creates substantial economic benefits. This approach not only lowers initial capital investments but also ensures faster returns on investment, which is particularly important for public and private investments in civil defense and protective construction projects.

Thus, the economic efficiency of 3D printing is based on a set of advantages: optimization of material use, automation of construction, reduction of work time, reduction of labor costs and the possibility of introducing environmentally friendly materials. These factors together provide a significant increase in the profitability of projects using additive technologies compared to traditional methods, which contributes to their widespread implementation in the field of civil protection and restoration of damaged structures.

Conclusions

The economic efficiency of 3D printing in construction is driven by multiple factors, including reduced material costs, shorter project timelines, and optimized labor usage. Through automation and precise digital control, 3D printing achieves significant cost reductions, making it particularly relevant for civil defense projects where rapid response and efficient restoration are critical.

In traditional construction, material costs dominate the budget, while 3D printing reduces material consumption by 40%, shortens construction time by 35%, and decreases labor requirements by 65%, confirming its high cost-effectiveness [2, p. 221; 8, p. 491].

Moreover, the ability to use recycled materials enhances environmental sustainability while lowering costs. This advantage is particularly significant for civil defense projects, where rapid deployment of protective structures is essential. Despite challenges such as material standardization and interlayer adhesion, ongoing advancements continue to improve the technology's applicability [16, p. 157].

Thus, additive technologies hold substantial potential for modern construction, particularly in the rapid restoration of damaged structures and the development of innovative solutions for civil defense. As the industry continues to evolve, the widespread adoption of 3D printing is expected to revolutionize the construction landscape, providing economically viable, sustainable, and efficient solutions.

3.3. Implementation of Energy-Efficient, Eco-Friendly, and Economical Materials in the Construction of Civil Defense Protective Structures

In modern construction, particularly within civil defense systems, the issue of environmental sustainability has become increasingly relevant. The use of eco-friendly materials not only reduces the environmental impact of construction but also optimizes raw material and energy consumption – factors that are critically important amid current economic and environmental challenges. The primary goal of implementing such materials is to replace traditional construction components with environmentally safe alternatives, thereby reducing CO_2 emissions, optimizing the use of natural resources, and ensuring the durability and reliability of structures.

One promising direction involves the use of secondary materials, such as recycled plastic and industrial by-products like fly ash and silica fume. For example, studies [8, p. 499] demonstrate that incorporating recycled plastic into self-compacting concrete not only reduces environmental impact but also ensures acceptable mechanical properties required for civil defense structures [2, p. 221]. Replacing a portion of cement with secondary materials reduces the consumption of primary resources and, consequently, the energy intensity associated with concrete production.

To formulate an eco-friendly concrete mixture, the component ratio is often described by the following formula:

$$\alpha = \frac{m_{eco}}{m_{total}}, \tag{3}$$

where α – the substitution coefficient, m_{eco} – represents the mass of environmentally friendly components (such as recycled plastic, fly ash, silica fume), and, m_{total} – the total mass of the mixture. According to research findings, the optimal value of α can be approximately 0.3, ensuring a balanced combination of economic and mechanical properties [2, p. 222]. Furthermore, an essential aspect involves the rheological characteristics of the mixtures, which determine the material's ability to be uniformly applied and maintain interlayer adhesion. These characteristics are evaluated using parameters such as the flow index T and the open time of the mixture t_{opent}. The rheological index can be conditionally described as:

$$R = \frac{T}{t_{open}}, \tag{4}$$

where R – is the rheological suitability index. An increase in R facilitates better material distribution across the structure, which is particularly crucial when using environmentally friendly components that may exhibit properties different from traditional materials [2, p. 224].

The use of eco-friendly materials also significantly reduces CO_2 emissions. Traditional cement production is highly energy-intensive, resulting in considerable greenhouse gas emissions. Incorporating secondary materials can reduce cement consumption by 30–40%, corresponding to a substantial decrease in CO_2 emissions. This relationship can be formally expressed by the following equation:

$$CO_{2_{eco}} = CO_{2_{trad}} \times (1 - \beta), \tag{5}$$

where CO_{2eco} – represents emissions when using environmentally friendly materials, CO_{2trad} – denotes the baseline emissions level, and β – the reduction coefficient, typically around 0.35 [9, p. 225].

Eco-friendly materials also influence the rheological properties of concrete mixtures. The key parameters include the mixture’s flow index T and open time t_{opent}, which ensure optimal material application. Although specific formulas for calculating the rheological index can be found in the literature, the core concept is that the addition of secondary components may alter these parameters, necessitating adjustments in the mixture composition to achieve optimal results [12, p. 101285].

The integration of environmentally friendly materials into protective structures represents a pivotal direction in modern construction. Utilizing secondary materials not only mitigates environmental impact but also reduces construction material costs and enhances the economic efficiency of projects.

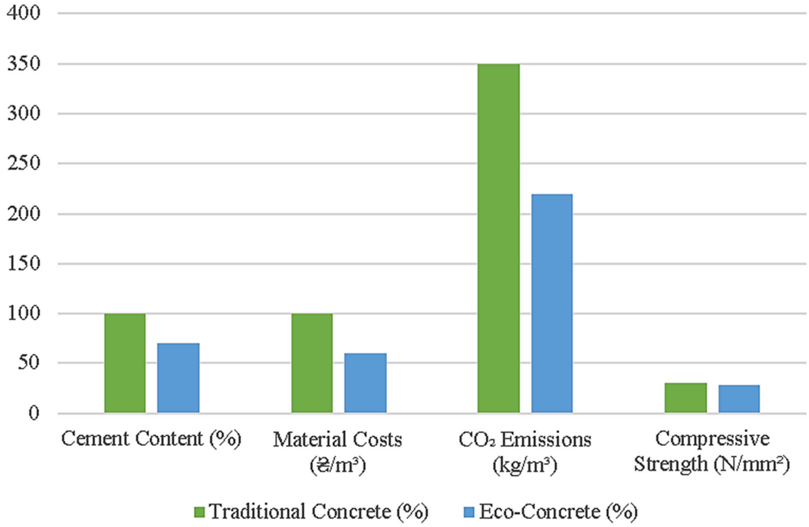

Figure 7. Comparison of cost-effectiveness of 3D printing and traditional construction

Source: [12, p. 101290]

As illustrated in *Figure 7*, the key advantages of eco-concrete include a 30% reduction in cement usage, which decreases the consumption of primary raw materials, a 35% reduction in material costs, ensuring significant savings on large-scale projects, and a 35% decrease in CO_2 emissions, contributing to the mitigation of the greenhouse effect and aligning with sustainable development principles. However, there is also a slight reduction in strength (approximately 7%), which is acceptable considering the other benefits. These findings demonstrate that the use of environmentally friendly materials in the construction of protective structures is not only feasible but also a necessary step toward enhancing the efficiency of the construction industry [8, p. 500].

Moreover, the adoption of material recycling technologies in construction opens new opportunities for optimizing production processes, reducing energy consumption, and increasing the durability of civil defense protective structures. This is particularly relevant for post-war infrastructure recovery and the rapid construction of facilities in crisis regions. The presented data confirm that eco-concrete is a promising direction for the development of protective structures, as it combines high technological efficiency with environmental safety and economic feasibility.

Another aspect of integrating environmentally friendly materials is their ability to enhance structural durability and resilience. For example, the use of self-compacting concrete enriched with silica fume ensures greater structural uniformity, positively impacting resistance to dynamic loads and mechanical stress [9, p. 223]. Such materials can reduce crack formation and improve interlayer adhesion, which is particularly critical for protective structures in high-risk areas.

An important factor is also the integration of eco-materials with modern monitoring and quality control technologies. For instance, current certification systems for protective structure components include additional criteria for environmental sustainability [8, p. 499]. These criteria facilitate the identification and optimization of mixtures containing secondary components, thereby reducing costs and enhancing the efficiency of structural restoration.

The application of environmentally friendly materials in protective structures also has a socio-economic impact. Lower material and production costs improve project profitability, which is particularly significant for large-scale restoration efforts in crisis situations. This allows both public and private investors to allocate resources efficiently, directing them toward infrastructure modernization and ensuring high levels of population safety [12, p. 101299].

The integration of eco-friendly materials into protective structures ensures significant savings in raw materials, reduces environmental impact, and optimizes construction costs. The use of secondary materials, such as recycled plastic, fly ash, and silica fume, lowers CO_2 emissions, contributing to the achievement of sustainable development goals. These approaches promote the creation of innovative, resilient, and economically viable solutions for civil defense systems, which is particularly crucial under modern emergency conditions and during military conflicts.

In light of the above, it can be concluded that integrating environmentally friendly materials into protective structures opens new prospects for modern construction development, ensuring enhanced quality, durability, and economic efficiency of civil defense facilities. Further research in this field will support the optimization of concrete mix compositions, the advancement of additive manufacturing technologies, and the implementation of new certification standards. These advancements, in turn, will ensure a high level of safety and environmental sustainability in construction under contemporary challenges [8, p. 502; 12, p. 101300; 25, p. 33].

3.4. Methods for Assessing Structural Durability Under Combined Loads

The durability of structures is defined by their ability to maintain functional properties under various loads, including static, dynamic, vibrational, and environmental influences. Of particular importance is the assessment of the durability of civil defense protective structures, which operate under elevated risk conditions, including the impact of blast waves, seismic loads, and aggressive environments [3, p. 24].

The primary methods for assessing structural durability include:

– Mechanical testing: Evaluation under compression, bending, and tensile stress.

– Damage analysis: Assessment of existing cracks and corrosion processes.

– Stochastic methods: Numerical modeling of material behavior using Monte Carlo simulations.

– Non-destructive testing methods: Ultrasonic testing, radiography, and acoustic emission.

Experimental Studies of Strength Under Combined Loads

Experimental methods enable the identification of critical loads at which material degradation occurs. For protective structures, particular attention is given to testing under:

– Multicyclic loading that simulates prolonged operational conditions.

– Impact waves and blast loads, assessing structural resilience.

– Corrosion resistance when exposed to aggressive environments.

To evaluate the structural strength under combined loads, the following equation is applied:

$$\sigma_{\text{eff}} = \frac{\sigma_{\text{stat}} + k_1 \cdot \sigma_{dyn} + k_2 \cdot \sigma_{\text{temp}}}{1 + k_3 \cdot \sigma_{\text{cor}}} \tag{6}$$

σ_{eff} – effective strength, σ_{stat} – effective strength, σ_{dyn} – dynamic load, σ_{temp} – temperature effect, σ_{kor} – temperature effect, k_1,k_2,k_3 – empirical coefficients accounting for the mutual influence of loads.

Use of Non-Destructive Testing Methods

Non-destructive testing (NDT) methods are employed to assess residual strength and predict service life by providing insights into the internal condition of structures without causing damage.

Key methods include:

– Ultrasonic testing: Detects internal defects in concrete and metal.

– X-ray testing: Used to diagnose cracks in load-bearing elements.

– Acoustic emission method: Monitors the development of microcracks under load.

– Thermal imaging scan: Identifies material structure irregularities.

Table 4 presents a comparison of non-destructive testing methods based on their effectiveness.

Table 4

Comparison of Non-Destructive Testing Methods for Structural Durability

Method	**Application Range**	**Detected Defects**	**Accuracy of Assessment**
Ultrasonic testing	Concrete, metal	Internal cracks	High
X-ray testing	Concrete, metal	Cracks, irregularities	High
Acoustic emission	Concrete, composites	Microcracks	Medium
Thermal imaging analysis	Concrete, metal	Moisture zones, voids	Medium

Source: [19, p. 1287]

Stochastic Modeling of Durability

Stochastic methods enable the prediction of structural failure probabilities based on random variations in material properties and applied loads. The reliability function used for calculations is expressed as:

$$P_f = \int_{-\infty}^{\sigma_{cr}} f(\sigma) d\sigma \qquad (7)$$

P_f – probability of structural failure, $f(\sigma)$ – material strength distribution, σ_{cr} – critical stress.

Durability analysis involves conducting statistical studies, including calculating material strength variation coefficients and stress distribution within structures [19, p. 1294].

Assessment of Structural Resilience Under Combat Conditions

Protective structures are exposed to blast waves, generating impulsive loads that may lead to structural failure. The equation for evaluating residual strength after an explosion is defined as:

$$\sigma_{rest} = \sigma_{init} - \Delta\sigma_{loss} \qquad (8)$$

σ_{rest} – residual strength after the explosion, σ_{init} – initial material strength, $\Delta\sigma_{loss}$ – strength loss due to dynamic loading.

Research has shown that reinforced concrete structures with specialized polymer coatings exhibit enhanced resistance to blast loads [4, p. 35].

Conclusion

Structural durability assessment methods rely on a combination of experimental testing, non-destructive control, and numerical modeling. For civil defense structures, it is critical to use materials with increased strength and resistance to combined loads. The application of modern methods extends the service life of protective structures and enhances their effectiveness under real-world operational conditions.

3.5. Application of Probabilistic Risk Models in Civil Defense Systems

In civil defense systems, risk assessment plays a critical role in minimizing threats to the population and enhancing the resilience of engineering structures. Probabilistic risk models are employed to analyze uncertainties in material properties, loads, and external factors that may lead to the loss of functionality in protective structures.

Probabilistic analysis methods include:

– Monte Carlo Method – Enables the evaluation of possible failure scenarios by iterative modeling of random variables [23, p. 18].

– Statistical Risk Analysis Methods – Used to calculate the probability of structural failure under varying load levels.

– Fault Tree Analysis – Identifies the most critical structural components and assesses their contribution to overall reliability [24, p. 320].

– Probabilistic Methods for Material Degradation Assessment – Used to calculate strength loss due to corrosion, fatigue, and combined load effects.

Monte Carlo Method in Risk Assessment

The Monte Carlo method is a fundamental tool for assessing structural reliability under stochastic conditions. It allows for simulating variable loads and predicting the likelihood of system failure.

Formally, the probability of structural failure can be expressed through the following function:

$$P_f = \frac{N_f}{N} \tag{9}$$

here P_f – probability of failure, N_f – number of simulations resulting in structural failure, N – total number of simulations.

The analysis considers the random values of stress σ and material strength σ_{kr}, which are typically distributed according to the normal or log-normal law:

$$P_f = P(\sigma > \sigma_{\text{kr}}) = \int_{\sigma_{\text{kr}}}^{\infty} f(\sigma)d\sigma. \tag{10}$$

Figure 8 graphically presents a comparison of failure probability values for different materials based on numerical modeling results.

Fault tree analysis identifies the most critical structural components that could lead to failure. It comprises nodes (events) connected by logical operators (AND, OR) to describe potential causes of failure.

To evaluate the system's probability of failure using logical analysis, the following equation is applied:

$$P_{\text{sys}} = 1 - \prod_{i=1}^{n} (1 - P_i), \tag{11}$$

P_{sys} – total system failure probability, P_i – probability of failure for each individual component, n – number of critical elements in the system.

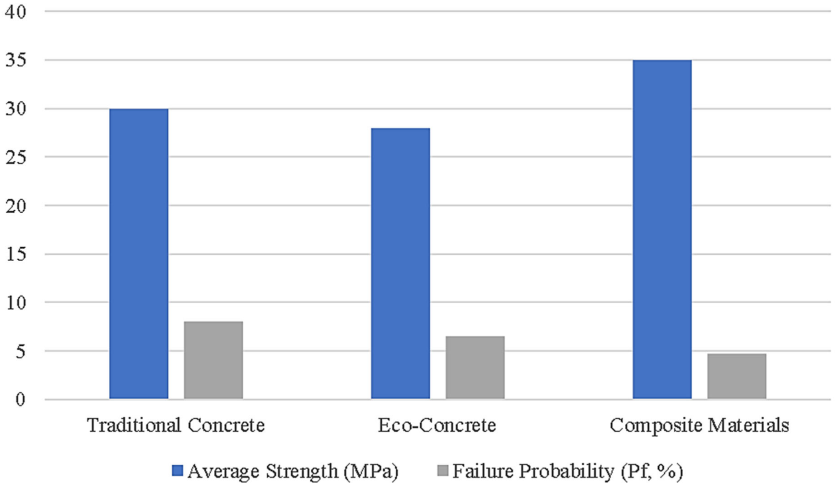

Figure 8. Results of Probabilistic Risk Analysis for Different Materials

Source: [23, p. 13]

For example, when analyzing protective structures, the most critical components include load-bearing walls, foundations, joints, and protective coatings. If the failure probabilities for these components are $P_1 = 0.02$, $P_2 = 0.03$, $P_3 = 0.01$ and $P_4 = 0.04$, the overall probability of structural failure will be:

$$P_{\text{sys}} = 1 - (1 - 0.02)(1 - 0.03)(1 - 0.01)(1 - 0.04) = 0.096.$$

This indicates that under such conditions, the probability of structural failure is 9.6%.

Probabilistic Risk Models Under Emergency Impact

Probabilistic risk analysis in civil defense systems involves evaluating structural failures under the influence of natural and technological hazards, such as seismic events, explosive loads, and thermal effects.

The risk level in the case of seismic impact can be assessed using the structural stability index:

$$R_s = \frac{\sigma_{\text{kr}}}{\sigma_{\max}}. \tag{12}$$

If $R_s < 1$, the structure cannot withstand the load. *Table 5* presents the risk assessment for different load types.

Table 5

Risk Level Analysis Under Combined Impacts

Load Type	Critical Strength Limit, MPa	Maximum Load, MPa	Stability Index RsRs	Risk Level
Seismic	25	22	1.14	Low
Explosive	30	35	0.86	High
Thermal	20	18	1.11	Low

Source: [16, p. 153]

Conclusions

The use of probabilistic models in civil protection systems allows to assess the probability of structural failure and identify the most critical elements that need strengthening, to ensure effective resource planning using the Monte Carlo method and statistical analysis to predict operational risks, to reduce the level of risk during the impact of emergencies by identifying the most vulnerable structural elements, to optimize structural solutions using probabilistic risk analysis to model the durability of structures. The use of such models allows to increase the efficiency of civil protection systems and ensure maximum safety of construction sites in case of extreme situations. Further research can be aimed at developing adaptive risk prediction algorithms and integrating artificial intelligence methods to increase the accuracy of risk assessment.

3.6. Forecasting and Optimization of Costs and Time for Structure Restoration

Restoring damaged structures, particularly civil defense facilities, requires a comprehensive approach to resource planning, task execution time optimization, and cost minimization. This task is further complicated by external factors such as limited availability of construction materials, unstable logistics chains, and adverse weather conditions.

Forecasting and cost optimization are carried out using the following methods:

– Resource management models – facilitate the determination of the optimal balance between available materials, workforce, and equipment [1, p. 67].

– Stochastic forecasting methods – used to analyze uncertainties that may affect the overall project duration and cost [5, p. 55].

– Automated cost control systems – applied to track changes in material costs and predict potential overruns.

– Work schedule optimization algorithms – integrated into construction management systems to shorten task completion times.

Stochastic Cost Forecasting

Stochastic methods enable the estimation of the possible range of restoration costs depending on external conditions. In general terms, the cost prediction for structure restoration can be expressed as:

$$C_{\text{prog}} = C_{\text{mat}} + C_{\text{work}} + C_{\text{logis}} + C_{\text{adm}} \tag{13}$$

C_{prog} – forecasted total cost, C_{mat} – material costs, C_{work} – labor costs, C_{logis}– transportation and logistics costs, C_{adm} – administrative costs.

To account for random price fluctuations, a stochastic approach is applied:

$$C_{\text{eff}} = C_{\text{prog}} \cdot (1 + k_{\text{inf}}), \tag{14}$$

where k_{inf} – inflation risk coefficient reflecting potential changes in material and labor costs

Optimization of Structure Restoration Time

The duration of restoration works depends on various factors, including resource availability, weather conditions, construction complexity, and decision-making speed. The critical path method (CPM) is used to estimate the minimum construction time:

$$T_{\text{min}} = \sum_{i=1}^{n} t_i \tag{15}$$

T_{min} – minimum possible task completion time, t_i – duration of each critical process.

To enhance schedule efficiency, the time compression method involves engaging additional resources:

$$T_{\text{opt}} = T_{\text{min}} - \frac{C_{\text{add}}}{C_{\text{econ}}} \tag{16}$$

T_{opt} – optimized task completion time, C_{add} – cost of additional resources, C_{econ} – savings from time reduction.

Table 6 presents a comparative analysis of restoration costs and time depending on the chosen strategy.

Table 6

Comparison of Cost and Duration of Structure Restoration by Different Approaches

Method	Cost, million UAH	Duration, days	Efficiency
Traditional Method	50	120	Baseline Level
Resource Optimization	45	100	Time Savings
BIM Integration	42	85	Most Efficient

Source: [16, p. 155]

BIM Integration for Cost and Time Forecasting

The use of Building Information Modeling (BIM) enables the automation of cost and project duration calculations by simulating various construction scenarios. The primary advantages of BIM include instant adaptation to changes in construction plans, cost reduction through optimized material usage, automated cost control, and schedule planning.

By employing BIM, the projected cost savings can be calculated as follows:

$$\Delta C = C_{\text{trad}} - C_{\text{BIM}} \tag{17}$$

ΔC – cost reduction, C_{trad} – cost of the traditional approach, C_{BIM} – cost of construction using BIM.

Automated Systems for Cost and Resource Control

Automation of the restoration process allows real-time cost monitoring and task plan adjustments. Key approaches include using drones for construction process monitoring, IoT (Internet of Things) for resource tracking, and machine learning-based cost forecasting.

Conclusions

Forecasting and optimizing the costs and time for structure restoration are key tasks in modern construction. The main methods that enhance efficiency include:

– Stochastic cost forecasting methods – help account for potential price fluctuations and prevent cost overruns.

– Work schedule optimization using CPM – reduces overall task completion time [1, p. 70].

– BIM integration – decreases construction costs and improves resource planning efficiency [5, p. 57].

– Automated monitoring systems – enhance control over construction processes and enable quick project adaptation to changing conditions.

Thus, the application of modern cost and time management methods is critically important for the successful restoration of damaged civil defense facilities, ensuring high-quality work at minimal cost and within the shortest possible time [24, p. 235].

Conclusions

Based on the conducted research, which encompasses a wide range of evaluation, restoration, and optimization methods for the construction and reconstruction of civil defense protective structures, several key conclusions can be drawn. These conclusions are essential for ensuring the durability, load resistance, and operational efficiency of such structures.

Optimal restoration of damaged structures requires a combined approach that integrates traditional methods with modern technologies, such as 3D printing and the use of energy-efficient, environmentally friendly materials. While traditional methods, like reinforcement application and standard calculation models, remain effective, they exhibit certain limitations, particularly when reconstructing damaged structures. Modern approaches significantly reduce costs and shorten recovery timelines, which is critically important for civil defense infrastructure [4, p. 36].

The implementation of advanced additive technologies in construction substantially increases the speed of erecting protective structures and enhances their adaptability to extreme operational conditions. 3D printing facilitates the use of novel composite materials characterized by high strength and adaptability to loads, including those resulting from explosive waves and seismic activity. Additionally, additive technologies contribute to significant material waste reduction, aligning with contemporary environmental standards and resource-saving practices [8, p. 503].

The application of eco-friendly materials in the construction and restoration of protective structures reduces the environmental impact of construction activities while enhancing economic efficiency. Research indicates that using recycled materials and specialized concrete additives not only diminishes the environmental footprint but also improves structural durability. For instance, replacing conventional cement with eco-friendly alternatives can reduce CO_2 emissions by 25–35% without significant loss in mechanical properties [25, p. 35].

Durability assessment methods under combined loads enable effective prediction of service life and facilitate the planning of necessary maintenance measures to keep structures in a safe condition. Analysis demonstrates that combining traditional tests, such as compression, tension, and bending tests, with non-destructive methods (ultrasonic testing, radiography, acoustic emission) provides the most comprehensive understanding of material condition and potential defects. The application of stochastic analysis allows for modeling material degradation processes and predicting residual service life [19, p. 1296].

Probabilistic risk models serve as effective tools for evaluating potential threats and predicting structural behavior under critical conditions. Methods such as Monte Carlo simulations, fault tree analysis, and numerical approaches help determine the likelihood of protective structure failure in emergency scenarios. Research findings confirm that the probabilistic modeling approach offers significantly greater accuracy than classical calculation models, as it accounts for material variability, random loads, and operational conditions [21, p. 203].

Forecasting and optimizing costs and recovery time are key tasks for ensuring the prompt restoration of critical civil defense facilities. Cost modeling using stochastic methods and resource management systems enables the efficient allocation of building materials, reduces project timelines, and minimizes cost overruns. The integration of Building Information Modeling (BIM) into the planning process significantly reduces calculation errors while enhancing the accuracy of cost and construction time predictions [23, p. 19].

The integration of automated control and monitoring systems significantly improves operational efficiency and facilitates timely detection of structural defects. The use of unmanned systems (drones), stress sensors, and artificial intelligence for structural monitoring allows for real-time detection of material changes, identification of critical damage, and development of effective mitigation measures.

The application of modern digital technologies in construction greatly enhances risk predictability and improves construction process management. The incorporation of big data and neural network algorithms into project design, construction, and operation enables the creation of adaptive monitoring systems capable of automatically adjusting safety parameters for structures [24, p. 237].

Acknowledgements

The work was carried out within the framework of the scientific and technical work "Resource-saving technologies for accelerated restoration of damaged buildings with the installation of civil defense protective structures", which was financed by the state budget of Ukraine (scientific work code No. 109/25; state registration number: 0125U000895).

References:

1. Altuwaim, A., & El-Rayes, K. (2018). Minimizing duration and crew work interruptions of repetitive construction projects. *Automation in Construction*, 88, 59–72. https://doi.org/10.1016/j.autcon.2017.12.024
2. Bos, F., Wolfs, R., Ahmed, Z., & Salet, T. A. M. (2016). Additive manufacturing of concrete in construction: Potentials and challenges of 3D concrete printing. *Virtual and Physical Prototyping*, 11(3), 209–225. https://doi.org/10.1080/17452759.2016.1209867
3. Viiskovyi standart 01.106.004 – 2018(01). (2018). *Inzhenerne zabezpechennia. Systema zahalnykh taktyko-tekhnichnykh vymoh do inzhenernoho ozbroiennia* [Engineering support. System of general tactical and technical requirements for engineering armament]. Ministry of Defense of Ukraine. (in Ukrainian).
4. Doroshenko, V. S., & Yanchenko, O. B. (2023). Metalevi nesuchi i hermetyzuiuchi konstruktsii dlia pidzemnykh ta zakhysnykh sporud [Metal load-bearing and sealing structures for underground and protective structures]. *Suchasni tekhnolohii, materialy i konstruktsii v budivnytstvi, 34(1)*, 27–35. https://doi.org/10.31649/2311-1429-2023-1-27-35 (in Ukrainian).
5. DSTU 9195:2022. (2023). *Shvydkosporudzhuvani zakhysni sporudy tsyvilnoho zakhystu modalnoho typu* [Rapidly erected protective structures of civil protection of modal type]. DP "UkrNDNC". (in Ukrainian).
6. Verkhovna Rada Ukrainy. (2015). *Zakon Ukrainy № 124-VIII. Pro tekhnichni rehlamenty ta otsinku vidpovidnosti* [Law of Ukraine No. 124-VIII. On technical regulations and conformity assessment]. Available at: https://zakon.rada.gov.ua/laws/show/124-19 (accessed February 2025). (in Ukrainian).

7. Verkhovna Rada Ukrainy. (2022). *Zakon Ukrainy № 2486-IX. Pro zabezpechennia vymoh tsyvilnoho zakhystu pid chas planuvannia ta zabudovy terytorii* [Law of Ukraine No. 2486-IX. On ensuring civil protection requirements during territory planning and development]. Available at: https://zakon.rada.gov.ua/laws/show/2486-20 (accessed February 2025). (in Ukrainian).

8. Feng, P., Meng, X., Chen, J.-F., & Ye, L. (2015). Mechanical properties of structures 3D printed with cementitious powders. *Construction and Building Materials,* 93, 486–497. https://doi.org/10.1016/j.conbuildmat.2015.05.132

9. Guo, N., & Leu, M. C. (2013). Additive manufacturing: Technology, applications and research needs. *Frontiers of Mechanical Engineering*, 8, 215–243. https://doi.org/10.1007/s11465-013-0248-8

10. Khalil, N., Aouad, G., & El Cheikh, K. (2017). Use of calcium sulfoaluminate cements for setting control of 3D-printing mortars. *Construction and Building Materials*, 157, 382–391. https://doi.org/10.1016/j.conbuildmat.2017.09.109

11. Verkhovna Rada Ukrainy. (2012). *Kodeks tsyvilnoho zakhystu Ukrainy* [Code of Civil Protection of Ukraine]. Available at: https://zakon.rada.gov.ua/laws/show/5403-17 (accessed February 2025). (in Ukrainian).

12. Liu, P., Yang, L., Gao, Z., Li, S., & Gao, Y. (2020). Use of recycled plastic in self-compacting concrete: A comprehensive review on fresh and mechanical properties. *Journal of Building Engineering*, 30, 101283. https://doi.org/10.1016/j.jobe.2020.101283

13. Mykhailovska, O. V., & Oleksienko, O. B. (2019). Zakriplennia stinok zakhysnykh sporud iz zastosuvanniam gruntotsementnykh elementiv [Fixation of protective structures walls using soil-cement elements]. *Visnyk Odes'koi derzhavnoi akademii budivnytstva ta arkhitektury, 75*, 44–52. https://doi.org/10.31650-2415-377X-2019-75-44-52 (in Ukrainian).

14. Ministry of Internal Affairs of Ukraine. (2018). *Nakaz MVS Ukrainy № 579. Pro zatverdzhennia vymoh z pytan vykorystannia ta obliku fondu zakhysnykh sporud tsyvilnoho zakhystu* [Order of the Ministry of Internal Affairs of Ukraine No. 579. On approval of requirements for the use and accounting of the fund of civil protection protective structures]. Available at: https://zakon.rada.gov.ua/laws/show/z0879-18 (accessed February 2025). (in Ukrainian).

15. Ministry of Reintegration of Ukraine. (2022). *Nakaz Ministerstva reintegratsii Ukrainy № 75. Perelik terytorialnykh hromad, shcho rozmishcheni v raioni provadennia boiovykh dii* [Order of the Ministry of Reintegration of Ukraine No. 75. List of territorial communities located in the combat zone]. Available at: https://www.minre.gov.ua/doc/doc/103 (accessed February 2025). (in Ukrainian).

16. Nekora, V. S., Nizhnyk, V. V., Pozdiev, S. V., Lutsenko, Yu. V., & Mykhailov, V. M. (2023). Osoblyvosti ta perspektyvy efektyvnoho funktsionuvannia zakhysnykh sporud tsyvilnoho zakhystu v umovakh boiovykh dii [Features and prospects of effective functioning of civil protection shelters in combat conditions]. *Naukovyi visnyk: Tsyvilnyi zakhyst ta pozhezhna bezpeka, 1(15)*, 149–157. https://doi.org/10.33269/nvcz.2023.1(15).149-157 (in Ukrainian).

17. Cabinet of Ministers of Ukraine. (2006). *Postanova Kabinetu Ministriv Ukrainy № 1764. Pro zatverdzhennia Tekhnichnoho rehlamentu budivelnykh vyrobiv (produktsii)* [Resolution of the Cabinet of Ministers of Ukraine No. 1764. On approval of the Technical Regulation of Construction Products]. Available at: https://zakon.rada.gov.ua/laws/show/1764-2006-п (accessed February 2025). (in Ukrainian).

18. Cabinet of Ministers of Ukraine. (2016). *Postanova Kabinetu Ministriv Ukrainy № 95. Pro zatverdzhennia moduliv otsinky vidpovidnosti ta pravyla vykorystannia moduliv otsinky vidpovidnosti* [Resolution of the Cabinet of Ministers of Ukraine No. 95. On approval of conformity assessment modules and rules for using conformity assessment modules]. Available at: https://zakon.rada.gov.ua/laws/show/95-2016-п (accessed February 2025). (in Ukrainian).

19. Pinchuk, N., Byba, V., Fraddosio, A., Castellano, A., Piccioni, M.D. (2024) Experimental and Numerical Study of the "Indirect" Reinforcement Systems for Masonry Walls Civil Engineering and Architecture, 12 (2), pp. 1282–1293. DOI: https://doi.org/10.13189/cea.2024.120243

20. Pinchuk, N., Byba, V. (2020) Experimental Investigation of Masonry and Reinforced Masonry Walls Under Local Loading. *Lecture Notes in Civil Engineering*, 73, pp. 205-213. http://doi:10.1007/978-3-030-42939-3_22

21. Usenko, D., Dovzhenko, O., Pohribnyi, V., Zyma, O. (2020) Masonry strengthening under the combined action of vertical and horizontal forces Proceedings of the 2020 Session of the 13th fib International PhD Symposium in Civil Engineering, pp. 193–199. ISBN: 978-294064306-6

22. Usenko D., Dovzhenko O., Pohribnyi V., Zyma O. (2020) Masonry strengthening under the combined action of vertical and horizontal forces. fib Symposium, pp. 193–199.

23. Usenko, V., Kodak, O. & Usenko, I. (2020). Geometric reliability model of the five site redundant structure. *Engineering Review,* 40 (2), 10–15. https://doi.org/10.30765/er.40.2.02

24. Usenko, V., Zinenko, T., Farzaliyev, S., Usenko, I., Kodak, O. (2023). The Model of a Technical System Operation at a Certain Time Interval. In: Onyshchenko, V., Mammadova, G., Sivitska, S., Gasimov, A. (eds) Proceedings of the 4th International Conference on Building Innovations. ICBI 2022. Lecture Notes in Civil Engineering, vol 299. Springer, Cham. https://doi.org/10.1007/978-3-031-17385-1_46

25. Wu, P., Wang, J., & Wang, X. (2016). A critical review of the use of 3-D printing in the construction industry. *Automation in Construction*, 68, 21–31. https://doi.org/10.1016/j.autcon.2016.04.005

26. Wolfs, R. J. M., & Salet, T. A. M. (2015). An optimization strategy for 3D concrete printing. In Proceedings of the 22nd EG-ICE Workshop (pp. 1–10). Eindhoven, The Netherlands.

27. Ministry for Regional Development of Ukraine. (2022). *DBN V.2.2-40:2018. Inkliuzyvnist budivel i sporud. Osnovni polozhennia* [DBN V.2.2-40:2018. Accessibility of buildings and structures. General provisions]. (in Ukrainian).

28. Ministry for Regional Development of Ukraine. (2023). *DBN V.2.2-5:2023. Zakhysni sporudy tsyvilnoho zakhystu* [Protective structures of civil protection]. (in Ukrainian).

29. Filipchuk, S. V., Nalepa, O. I., Holub, A. O., & Baran, D. Ya. (2023). Analiz isnuiuchykh arkhitekturno-konstruktyvnykh rishen zakhysnykh fortyfikatsiinykh sporud [Analysis of existing architectural and structural solutions for protective fortification structures]. *Resursoekonomni materialy, konstruktsii, budivli ta sporudy, 43*, 228–237. https://doi.org/10.31713/budres.v0i43.25 (in Ukrainian).

30. Shtepa, K. O. (2014). *Metody i modeli formuvannia bezpechnoho seredovyshcha zhyttiediialnosti naselennia* [Methods and models of safe environment formation for human life safety]. (Author's abstract of the dissertation for obtaining the scientific degree of Candidate of Technical Sciences). Kyiv. (in Ukrainian).