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ADDITIVE TECHNOLOGIES IN CONSTRUCTION: TECHNICAL, ECONOMIC AND MANAGEMENT ANALYSIS

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Abstract. *The study is devoted to a comprehensive analysis of the introduction of additive technologies into modern construction production, revealing the technical, economic, and managerial aspects of concrete 3D-printing of architectural structures. The work systematically analyzes the evolution of additive manufacturing technologies and identifies the main structural types of 3D-printers (an additive machine for layer-by-layer construction of objects), including portal, robotic, mobile, and hybrid systems. A detailed study of the technological parameters of concrete 3D-printing with concrete mixtures is presented, in particular, optimal printing speed modes, layer parameters, criteria for shaping and quality of building structures. A comparative analysis of the technological capabilities of leading world equipment manufacturers, such as ICON, COBOD International, Apis Cor, and WinSun, is conducted. The economic analysis demonstrates significant advantages of additive technologies: reduction of construction time by 2-6 times, reduction of construction cost by 20-35%, and increase in the load-bearing capacity of structures. The study comprehensively explores the structure of capital and operational expenses associated with technology implementation. Special emphasis is placed on the management aspects of introducing additive technologies, highlighting the critical need for an interdisciplinary approach and knowledge integration across architecture, engineering, management, and computer modeling. The study determines the prospects for the development of concrete 3D-printing technology in the construction industry and outlines the main directions of further scientific research and practical implementation of innovative solutions. This study was developed between the Department of "Integrated Technologies of Mechanical Engineering" named after M. Semko of NTU "KhPI" and "Geopolimer" LTD to implement innovative technologies in the construction industry.*

Keywords: *concrete 3D printing; construction; economic efficiency; project management; building materials.*

1. Introduction

The introduction of additive technologies (concrete 3D-printing) into construction is driven by many global challenges and industry needs. First, the global construction industry is facing an acute need for rapid and cost-effective housing construction [1].

Second, the construction sector is one of the largest consumers of natural resources. Additive technologies offer the potential for significant reduction of construction waste and optimization of material use. Third, there is a shortage of skilled labor in the construction sector. Automation of construction processes through concrete 3D-printing allows for partially addressing this issue. Moreover, the relevance of using additive technologies is underscored by the following factors:

- growing requirements for building energy efficiency;
- the need for rapid infrastructure restoration in post-conflict zones and disaster-affected areas;
- the requirement to create complex architectural forms while reducing their implementation costs;
- a trend towards individualization of housing construction and project adaptation to specific customer needs.

From a technological perspective, recent advancements in materials science, robotics, and CAD/CAM technologies create favorable conditions for the widespread implementation of additive technologies in construction. New construction mixtures optimized for concrete 3D-printing have been developed, along with improved quality control systems and automation of layer-by-layer forming processes [2–4].

However, despite the obvious potential, the widespread adoption of additive technologies in construction is constrained by several technical, economic, and managerial challenges that require comprehensive analysis and development of appropriate solutions. This necessitates a comprehensive study of the possibilities and limitations of additive technologies in the context of modern construction.

2. Review of the literature

The state of studying additive technologies in construction is characterized by diverse and interdisciplinary approaches. Technical aspects of concrete 3D-printing of building structures have been explored in works [1–5], which focused on developing optimal construction mixture compositions [4] and technological printing parameters [5, 6]. In the work [7] presented the main scientific research directions for technological aspects of layer-by-layer construction using cement mixtures. Researchers from China, the United States, and Australia have been the most active in this research direction (in order of decreasing publication volume). Now Germany, France, Netherlands, and England are the leaders in Europe. The largest number of publications in journals: Construction and Building Materials, Cement and Concrete Composites, Materials, Cement and Concrete Research, Automation in Construction, Additive Manufacturing [8].

Economic aspects of additive technology implementation were examined in the work [9]. Studies [10] are dedicated to comparative cost analysis of traditional and additive construction. Project management issues using concrete 3D-printing were investigated in [11], focusing on the specifics of planning and organizing the construction process.

A particularly well-developed research direction is determining the rational composition of concrete mixtures depending on multiple factors and the physical-mechanical characteristics of concrete samples [12].

If we count by the number of publications in Google Scholar, the greatest scientific contributions to additive construction technologies were made by: Ma Guowei, Wang Li, Sanjayan Jay, Xiao Jianzhuang, Mechtcherine Viktor, Tan Ming Jen, Panda Biranchi, De Schutter Geert, Schlangen Erik, Zhang Yamei.

Despite the significant volume of research, there remains a need for a comprehensive analysis of the interconnections between technical and technological capabilities, economic efficiency, and management aspects of implementing additive technologies in construction.

The work aims to identify research directions for developing a comprehensive approach to evaluating the effectiveness of implementing additive technologies in construction, based on the integration of technical, economic, and management analysis.

3. Modern design solutions of 3D-printers for additive manufacturing of concrete structures

Additive technologies in construction are currently experiencing a stage of active development, where specialized 3D-printers for working with concrete play a key role. The main structural types of such printers include [1, 2]:

- portal structures with a fixed frame (extruder movement along Cartesian *X*, *Y*, and *Z* axes; provide high printing accuracy and process stability; used for small architectural forms and construction structures);
- portal structures with fixed or movable vertical structures and displacement of two longitudinal and/or one transverse beam (provide sufficiently high precision and printing productivity; used for obtaining large building structures);
- robotic manipulators (based on multi-axis industrial robots, allowing printing of complex spatial structures. Have higher flexibility compared to portal systems, but require more complex software and have lower productivity);
- mobile concrete 3D printers (design allows autonomous movement and installation on various surfaces; for rapid construction of temporary structures);

- hybrid systems (combine properties of different concrete printer types, ensuring maximum adaptability to various architectural and construction tasks).
- All concrete printer types allow combining traditional construction methods with additive technologies.

Each printer type has specific advantages and limitations, the selection of which depends on specific project requirements, building geometry, and production conditions.

The main criteria for equipment selection and comparison include:

- printing accuracy (positioning and shape formation errors);
- workspace dimensions (possible building sizes);
- extruder movement productivity and speed (construction time);
- equipment mobility (preparation time for transportation, assembly time, transportation requirements);
- equipment and operational costs.

Research directions are aimed at improving concrete 3-D printer structural parameters, expanding their functional capabilities (parallel extruder or nozzle operation, reinforcement during extrusion), diversifying nozzle and leveling knife designs, reducing shape formation errors, and developing diagnostic and construction process monitoring systems.

The subsequent details are considered for portal printers (Fig. 1), which are among the most promising design solutions for rapidly restoring Ukraine's infrastructure.

Figure 1 – Concrete 3D-printer GP-1 (manufacturer "Geopolimer" LTD, Kharkiv)

4. Technological parameters of the concrete 3D printing

When determining the technological capabilities of additive technologies in construction, the primary focus was on the shape formation mode parameters [2].

Printing speed V. Based on the practical experience of large-format construction printer developers, the optimal printing speed range is $V = 50$-150 mm/s. The maximum speed can reach up to 1000 mm/s (depending on mixture composition, layer width, and height [4]). Minimum speed: not less than 30 mm/s (to prevent material solidification). Speed is primarily determined by mixture composition and extruder productivity. Key factors influencing speed [13] include concrete mixture viscosity, cement setting time, mixture supply pressure, nozzle diameter, and ambient temperature.

Layer parameters: thickness h and width b.

Layer thickness h. The optimal range is considered to be 8–50 mm, with typical values for vertical walls being 15–20 mm; h mainly depends on layer width, nozzle diameter, and mixture rheological properties.

Layer width b. Recommended range is b = 20–60 mm, ensuring a rational b/h ratio of 2.5–4.0. This b/h ratio is necessary to ensure a stable layer and overall structure dimensions. The maximum possible b value is 300 mm. The b values depend on nozzle diameter, supply pressure, printing speed, and surface inclination angle a.

Permissible wall surface inclination angle range (without additional support) a_c = 75°–90°, with vertical walls providing the greatest structural stability, i.e., at a_c = 90°. With support, it is practically feasible across the entire a_c range.

Factors influencing the permissible angle a_c (without support): layer thickness, mixture setting speed, previous layer strength, structure height, temperature conditions, and mixture composition.

Additional technological parameters include:

- layer construction interval $t_{\mathrm{min\_l}}$ (necessary for ensuring stable shape formation), optimal interval $t_{\mathrm{min\_l}}$ = 1–10 minutes, depending on mixture composition, structure height, and environmental conditions;
- environmental conditions: temperature (optimal -15°C … -25°C, recommended range 5°C… -40°C), humidity (optimal -50% … -70%), protection from direct sunlight and wind.

5. Comparative analysis of technological capabilities of concrete 3D printing equipment

Analysis of the technological capabilities of market-leading additive equipment reveals the following features:

ICON Technology:

- printing speed up to 2000 mm/s;

COBOD International:

- modular BOD2 system with broader scaling capabilities;
- printing speed up to 1000 mm/s;

Apis Cor:

- mobile printer with a printing radius of up to 8.5 meters;
- ability to print curved surfaces;

WinSun (Yingchuang):

- large-scale systems for extensive projects;
- capability to print multi-story buildings;
- material recycling;

Generally for most manufacturers:

- proprietary material developments;
- operation in challenging weather conditions (advantages for ICON);
- integrated quality control system (advantages for ICON);
- multifunctional extruder;
- ability to work with a wide range of materials (advantages for COBOD International);
- high positioning accuracy (advantages for COBOD International and Apis Cor).

In cases of printing under extreme conditions (low or high temperature and/or humidity), key technological innovations can be separately highlighted:

Materials:

- special additives for rapid setting at low temperatures;
- viscosity modifiers for high-temperature operations;
- reinforcing components to increase early-stage strength;

Material supply system:

- thermal insulation of transport line;
- heating/cooling of material during transportation;
- moisture control system for components;
- automatic mixture composition adjustment;

Extruder:

- nozzle thermal stabilization system;
- protection against abrasive wear;
- dynamic extrusion diameter control;
- cleaning system during stops;

Control system (electronics):

- compensation for structural thermal deformations;
- adaptive calibration system;
- vibration and position correction sensors;
- enhanced drives for operation during strong winds;

Control system (software):

- external factor compensation algorithms;
- predictive print quality analytics;
- adaptive speed management;
- material structural integrity monitoring.

Due to these innovations, the working conditions are considered:

ICON (Vulcan system):

- temperature range from +2°C to +43°C;
- relative humidity 20–95% (with compensation systems);

COBOD (BOD2 system):

- temperature range from +5°C to +40°C;
- relative humidity 30–85%.

Research directions: optimizing extruder speed and acceleration depending on movement trajectory, mixture composition, and environmental conditions; predicting, monitoring, and preventing extruder movement jolts; optimizing building design for specific equipment technological capabilities; optimizing trajectory and construction time based on surface quality criteria.

6. Print quality criteria

There are several important quality criteria for 3D printing of buildings, based on various technical standards. The main requirements include:

- verticality of the walls, the maximum deviation from the vertical should not exceed 1/200 of the wall height (for a 3 m high wall, the permissible deviation is approximately 15 mm);
- horizontality of the surfaces, the maximum deviation from the horizontal is 1/300 of the length (for a 6 m section, the permissible deviation is approximately 20 mm);
- wall thickness, the permissible deviation is ±5…10 mm from the design thickness (it is important to ensure uniformity over the entire height);
- straightness (along the surface of the layer), on an arbitrary section of 2 meters the maximum deviation is no more than 10–12 mm, the total curvature along the length of the wall should not exceed 20 mm;

- corner joints, deviation of corners from the design position should not exceed 5–7 mm;
- minimum concrete strength, 20–40 MPa;
- bond strength between layers, not less than 1.5–2 MPa;
- absence of delaminations;
- homogeneity of the concrete mix (the mix should be free of pores and cavities, with a material density of no less than 97%, and a uniform distribution of reinforcing elements).

7. Economic Aspects of Implementing Additive Technologies

According to research [14], the main capital costs associated with the implementation of additive technologies in construction are as follows:

- construction 3D printer – 40…60% of the total investment;
- material mixing and feeding systems – 15…25%;
- software and control systems – 10…20%;
- auxiliary equipment, tools and consumables – 5…15%.

The distribution of operating costs for such technologies typically follows this structure [15]:

- materials – 30…45%;
- labor costs – 20…35%;
- energy consumption – 5…10%;
- maintenance – 10…15%;
- logistics – 5…10%.

An analysis of the indicators for the most common construction technologies, based on the example of a 100 m² private house, has led to the following results, which are presented in Table 1.

A comparative analysis of construction technology characteristics (Table 1) highlights several advantages of 3D printing, particularly in constructing walls with a rectilinear configuration.

The fundamental advantages of the technology include:

- reduction of construction time (for example, 3D printing technology allows to reduce the duration of wall construction by 2–6 times compared to traditional methods – masonry, aerated concrete).
- reduced load on the foundation and greater bearing capacity (a comparative analysis shows that 3D printing technology provides significantly higher bearing capacity indicators (2457.2 kN) with lower specific material consumption (0.185–0.235 m³ per 1 m² of wall)).

- economic efficiency (the cost of 1 m² of wall using 3D printing technology is 115–135 US dollars, which is 20–35% lower than traditional technologies).

Additional technological advantages include:

- the possibility of integrated insulation without the need for additional structural elements;
- elimination of the need for external and internal finishing;
- architectural variability, enabling the individualization of structural solutions.

Table 1 Comparison of indicators of the construction of the walls of the house per 100 m^2 obtained by different technologies

Construction technology	Relative indicators (with a wall height of 3.0 m)				Construction time (days)
	weight (kg / m^2)	permissible load (kN)	volume per m² (m³)	min cost ($/m²)	
Stone masonry – brick, 51 cm wide	918	881	0,51	180	25
Construction of aerated concrete	450	1500	0,4	150	10-12
3D printing of a wall, 40 cm wide	370	2457	0,185	115	4
3D printing of a wall, 60 cm wide	470	2457	0,235	135	5
3D printing of a wall, 50 cm wide, reinforced concrete (pouring)	1200	2 800–3 000	0,5	210	5
Monolithic house, formwork 50 cm wide, reinforced concrete (pouring)	1250	2 800–3 000	0,5	180–230	10-14

Note: The cost is indicated based on 2024 prices.

These advantages confirm the prospects of 3D printing technology in the construction industry, especially in countries with developed innovation infrastructure (USA, Netherlands, Western European countries).

Further research is needed on the issues of long-term operation, the influence of climatic factors, and the adaptation of the technology to various construction conditions.

8. Project Management for Additive Technologies in Construction

The introduction of additive technologies into the construction industry necessitates a fundamentally new approach to project management that accounts for the specific requirements of 3D printing architectural structures.

The main components of project management include:

- planning and preparation (special tasks of 3D modeling of an architectural object, preliminary calculation of material consumption, selection of optimal printing technology, preparation of specialized equipment);
- technological features of management (control of printing mixture parameters, monitoring the accuracy of architectural form reproduction, printing management, ensuring printing conditions);
- resource provision (training of qualified personnel, maintenance of 3D printers, material logistics, equipment calibration);
- economic efficiency (optimization of construction time reduction, minimization of labor costs, production waste, and project estimates);
- risk management (forecasting possible technological limitations, insurance of project risks, ensuring the quality of the final design, testing of test samples).

A key aspect is the establishment of an integrated management system that combines technological innovations, economic efficiency, and engineering solutions.

Promising directions for further research include the development of unified management standards.

The implementation of additive technologies requires an interdisciplinary approach, integrating knowledge from architecture, engineering, management, and computer modeling.

9. Conclusions

Additive technologies in construction are at the stage of active development, demonstrating significant potential for transforming this industry.

Modern 3D printers are represented by various design types: gantry, robotic, mobile, and hybrid systems, each with specific advantages and limitations.

The key technological parameters of concrete 3D printing are speed (50–1000 mm/s), layer thickness (5–50 mm), layer width (20–300 mm), and surface inclination angle (75°–90°).

Leading manufacturers of 3D printers (ICON, COBOD, Apis Cor, WinSun) demonstrate unique technological solutions, particularly high speed, mobility, and adaptability of equipment.

3D printing technology offers several advantages over traditional construction methods, including:

- a reduction in construction time by 2–6 times;
- a decrease in the load on the foundation;
- high load-bearing capacity of structures;
- economic efficiency, with cost reductions of 20–35%.

Clear quality requirements for 3D printing have been established, encompassing:

- permissible deviations from vertical and horizontal alignment;
- specifications for wall thickness;
- criteria for the strength and uniformity of the concrete mix.

The distribution of capital costs for implementing this technology has been analyzed, with the largest share attributed to equipment expenses. A distinctive feature of budgeting for additive technologies is the significant proportion of material costs, accounting for 30–45%.

The adoption of additive technologies necessitates a novel, integrated management approach that combines technological innovation, economic efficiency, and engineering solutions. An interdisciplinary effort is essential, requiring collaboration among specialists in architecture, various engineering disciplines (e.g., design, mechanics, electronics, technology, programming), management, and computer modeling.

Additive 3D printing technologies demonstrate revolutionary potential in the construction industry, offering more efficient, economical, and flexible solutions compared to traditional methods.

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АДИТИВНІ ТЕХНОЛОГІЇ В БУДІВНИЦТВІ: ТЕХНІЧНИЙ, ЕКОНОМІЧНИЙ ТА МЕНЕДЖМЕНТ-АНАЛІЗ

Анотація. *Дослідження присвячене комплексному аналізу впровадження адитивних технологій у сучасне будівельне виробництво, розкриваючи технічні, економічні та управлінські аспекти 3D-друку архітектурних конструкцій. Актуальність використання адитивних технологій підкреслюється наступними факторами: зростання вимог до енергоефективності будівель; необхідність швидкого відновлення інфраструктури в постконфліктних зонах та районах стихійних лих; потреба у створенні складних архітектурних форм при зниженні вартості їх реалізації; тенденція до індивідуалізації житлового будівництва та адаптації проектів під конкретні потреби замовників. У роботі системно проаналізовано еволюцію технологій адитивного виробництва, визначено основні конструктивні типи 3D-принтерів, включаючи портальні, роботизовані, мобільні та гібридні системи. На сьогодні у світі відомо близько 500 виробників будівельних 3D принтерів. Представлено детальне дослідження технологічних параметрів 3D-друку бетонними сумішами, зокрема оптимальних режимів швидкості друку, параметрів шарів, критеріїв формоутворення та якості будівельних конструкцій. Проведено порівняльний аналіз технологічних можливостей провідних світових виробників обладнання, таких як ICON, COBOD International, Apis Cor та WinSun. Економічний аналіз демонструє значні переваги адитивних технологій по відношенню до інших, які широко поширені у будівництві: скорочення термінів будівництва у 2 – 6 разів, зниження собівартості будівництва на 20 – 35 %,* *підвищення несучої здатності конструкцій, зменшення навантаження на фундамент. Розкрито структуру капітальних та операційних витрат при впровадженні технології. Основними технологічними параметрами 3D-друку бетонними сумішами є швидкість друку (50 – 1000 мм/с), товщина шару (8 – 50 мм), ширина шару (20 – 300 мм) та кут нахилу поверхні (75° –90°). Особливу увагу приділено управлінським аспектам впровадження адитивних технологій, необхідності міждисциплінарного підходу та інтеграції знань з архітектури, інженерії, менеджменту та комп'ютерного моделювання. Дослідження визначає перспективи розвитку технології 3D-друку в будівельній галузі, окреслює основні напрямки подальших наукових досліджень та практичного впровадження інноваційних рішень. Дослідження виконано в рамках науково-технічного співробітництва між кафедрою «Інтегровані технології машинобудування» ім. М.Ф. Семка» НТУ «ХПІ» та ТОВ «Геополімер» з метою впровадження інноваційних технологій в будівельну галузь.*

Ключові слова: *3D друк бетону; будівництво; економічна ефективність; управління проектами; будівельні матеріали.*