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REVIEW ARTICLE

3D PRINTING IN THE ARCHITECTURE OF KAZAKHSTAN: FROM EXPERIMENTAL HOUSES TO SUSTAINABLE SOLUTIONS

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Abstract. *The analysis of the potential of introducing 3D printing technology into the architectural and construction practice of the Republic of Kazakhstan includes examples of the implementation of 3D-printed buildings both in the international arena (the Netherlands, Angola) and in Kazakhstan. The article considers the possibility of introducing 3D printing into national practice with an emphasis on sustainability, adaptability and energy efficiency. The purpose of the study is to assess the technological readiness and practical applicability of 3D-printed solutions in the context of Kazakhstan. The work uses a comparative analysis of international and domestic projects, a review of relevant literature, a study of the engineering characteristics of materials and mixtures, as well as interviews with specialists. Projects such as Milestone, Power2Build, and local implementations using COBOD printers are considered as the main examples. The advantages of 3D-printed solutions using local materials are revealed: reduction of construction time and labor costs, improvement of thermal engineering parameters of enclosing structures and reduction of carbon footprint. The ability of the technology to form complex geometries, provide integrated thermal insulation and adapt to earthquake-prone conditions is shown. The prospects of biodegradable composites and digital workflows (BIM/CAM, parametric design) are noted. 3D printing has already moved into the category of applied technologies ready to scale in Kazakhstan, subject to standardization of formulations, development of a regulatory framework and training of personnel. The technology offers economic and environmental benefits, especially for remote and seismically hazardous regions, and can become a tool for mass sustainable housing construction. The authors offer recommendations on the adaptation of mixtures to climatic conditions, the development of standards and the integration of educational programs to accelerate the introduction of technology and ensure the quality of construction. Further research should focus on the durability of printed structures and the economic assessment of large-scale projects.*

Keywords: *3D printing, architecture, sustainable construction, adaptability, biodegradable materials, energy efficiency, digital design*.

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ШОЛУ МАҚАЛА

ҚАЗАҚСТАН СӘУЛЕТІНДЕГІ 3D-БАСПА: ЭКСПЕРИМЕНТТІК ҮЙЛЕРДЕН ТҰРАҚТЫ ШЕШІМДЕРГЕ ДЕЙІН

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Аңдатпа. *Қазақстан Республикасының сәулет және құрылыс практикасына 3D-баспа технологиясын енгізу әлеуетін талдау халықаралық аренада (Нидерланды, Ангола), сондай-ақ Қазақстанда 3D-баспа ғимараттарын іске асыру мысалдарын қамтиды. Мақалада тұрақтылыққа, бейімделуге және энергия тиімділігіне назар аудара отырып, ұлттық тәжірибеге 3D басып шығаруды енгізу мүмкіндігі қарастырылады. Зерттеудің мақсаты-Қазақстан контекстінде 3D-баспа шешімдерінің технологиялық дайындығы мен практикалық қолданылуын бағалау. Жұмыста халықаралық және отандық жобаларды салыстырмалы талдау, бейіндік әдебиеттерге шолу, материалдар мен қоспалардың инженерлік сипаттамаларын зерттеу, сондай-ақ мамандармен сұхбат пайдаланылды. Негізгі мысалдар ретінде Milestone, Power2Build сияқты жобалар, сондай-ақ COBOD принтерлерін қолдана отырып жергілікті іске асыру қарастырылады. Жергілікті материалдарды пайдалану кезінде 3D басып шығару шешімдерінің артықшылықтары анықталды: құрылыс мерзімдері мен еңбек шығындарын қысқарту, қоршау конструкцияларының жылу техникалық көрсеткіштерін жақсарту және көміртегі ізін азайту. Технологияның күрделі геометрияны қалыптастыру, интеграцияланған жылу оқшаулауын қамтамасыз ету және сейсмикалық қауіпті жағдайларға бейімделу қабілеті көрсетілген. Биологиялық ыдырайтын композиттер мен цифрлық жұмыс процестерінің (BIM/CAM, параметрлік дизайн) болашағы атап өтілді. 3D-басып шығару құрамдарды стандарттау, нормативтік базаны әзірлеу және кадрларды даярлау шартымен Қазақстанда масштабтауға дайын Қолданбалы технологиялар санатына енді. Авторлар технологияны жеделдетіп енгізу және құрылыс сапасын қамтамасыз ету үшін қоспаларды климаттық жағдайларға бейімдеу, стандарттарды дамыту және білім беру бағдарламаларын біріктіру бойынша ұсыныстар ұсынады. Әрі қарайғы зерттеулер басылған конструкциялардың беріктігіне және ауқымды жобаларды экономикалық бағалауға бағытталуы керек.*

Түйін сөздер: *3D басып шығару, сәулет, тұрақты құрылыс, бейімделу, биологиялық ыдырайтын материалдар, энергия тиімділігі, цифрлық дизайн.*

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ОБЗОРНАЯ СТАТЬЯ

3D-ПЕЧАТЬ В АРХИТЕКТУРЕ КАЗАХСТАНА: ОТ ЭКСПЕРИМЕНТАЛЬНЫХ ДОМОВ К УСТОЙЧИВЫМ РЕШЕНИЯМ

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Аннотация. *Анализ потенциала внедрения технологии 3D-печати в архитектурную и строительную практику Республики Казахстан включает примеры реализации 3D-печатных зданий как на международной арене (Нидерланды, Ангола), так и в Казахстане. В статье рассматривается возможность внедрения 3D-печати в национальную практику с акцентом на устойчивость, адаптивность и энергоэффективность. Цель исследования - оценить технологическую готовность и практическую применимость 3D-печатных решений в контексте Казахстана. В работе использованы сравнительный анализ международных и отечественных проектов, обзор профильной литературы, изучение инженерных характеристик материалов и смесей, а также интервью со специалистами. В качестве основных примеров рассмотрены такие проекты, как Milestone, Power2Build, а также локальные реализации с применением принтеров COBOD. Выявлены преимущества 3D-печатных решений при использовании местных материалов: сокращение сроков строительства и трудозатрат, улучшение теплотехнических показателей ограждающих конструкций и снижение углеродного следа. Показана способность технологии формировать сложную геометрию, обеспечивать интегрированную теплоизоляцию и адаптироваться к сейсмоопасным условиям. Отмечена перспективность биоразлагаемых композитов и цифровых рабочих процессов (BIM/CAM, параметрический дизайн). 3D-печать уже перешла в разряд прикладных технологий, готовых к масштабированию в Казахстане при условии стандартизации составов, разработки нормативной базы и подготовки кадров. Авторы предлагают рекомендации по адаптации смесей к климатическим условиям, развитию нормативов и интеграции образовательных программ для ускоренного внедрения технологии и обеспечения качества строительства. Дальнейшие исследования должны сосредоточиться на долговечности напечатанных конструкций и экономической оценке масштабных проектов.*

Ключевые слова: *3D-печать, архитектура, устойчивое строительство, адаптивность, биоразлагаемые материалы, энергоэффективность, цифровое проектирование.*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

АЛҒЫС / ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу жеке қаржыландыру көздерін пайдалана отырып жүргізілді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось с использованием частных источников финансирования.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

1 INTRODUCTION

Modern architecture increasingly turns to technologies that are capable not only of shaping new aesthetic solutions but also of responding to the challenges of sustainable development, energy efficiency, and environmental safety. One of the most promising technologies in this field is 3D printing, which in recent years has evolved from an experimental method into a fully-fledged tool of architectural and construction practice. Its advantages are evident: the ability to construct buildings within shorter timeframes, reduce construction waste, employ innovative materials, and create complex forms that are unattainable by conventional construction methods.

The relevance of this study is determined by the need to understand how 3D printing technologies can be integrated into the architectural practice of Kazakhstan, taking into account the country's natural, climatic, and cultural factors.

The aim of the research is to analyze the potential of applying 3D printing and innovative materials in Kazakhstan's construction sector and to identify their role in shaping a sustainable architectural environment.

The scientific novelty of the study lies in a comprehensive approach to examining 3D printing not only as an engineering and technical tool but also as a driver of architectural and cultural transformation. For the first time, the technology is considered in the context of Kazakhstan's climatic conditions and cultural traditions, which makes it possible to propose ways of adapting it and outlining prospects for further development.

2. LITERATURE REVIEW

Research confirms that 3D concrete printing is a well-established process, encompassing digital modeling, mix preparation, and layer-by-layer material deposition **(Gosselin et al., 2016; Buswell et al., 2018)**. Key parameters include rheology, extrusion speed, and interlayer bonding, which influence strength and accuracy **(Wolfs, Bos, & Salet, 2019; Meurer & Classen, 2021)**. Dry mixes and modified cementitious composites with functional additives are actively being developed (Le et al., 2012; Paul et al., 2018). There is growing interest in local materials (clay, earth) and biodegradable composites (PLA, PHAs) to reduce carbon footprint **(Kolesnikova & Alguzhina, 2021; Tkachenko et al., 2025; Pineiro, 2025)**. Projects like Milestone (Netherlands) and Power2Build (Angola) demonstrate the successful application of 3D printing for creating energy-efficient buildings with complex geometries and addressing housing shortages **(Walsh, 2018; Souza, 2021; Frearson, 2018; Pineiro, 2025)**. The experience of BM Partners 3D Print in Kazakhstan confirms the feasibility of constructing earthquake-resistant buildings adapted to local conditions (authors' materials). Digitalization of processes through CAD/BIM/CAM allows for optimized design and production, translating architectural solutions into machine code **(Buswell et al., 2018; Raphael et al., 2022)**. 3D printing offers time and resource savings, as well as environmental benefits through the use of optimized and local materials **(Strohle et al., 2023; Souza, 2021)**. However, barriers exist due to a lack of standards, regulatory frameworks, and data on long-term performance in diverse climatic conditions **(Strohle et al., 2023; Zareiyan & Khoshnevis, 2021)**. For Kazakhstan, relevant research areas include seismic resistance, energy efficiency, adaptation of technologies to local conditions, and the development of national standards **(Le et al., 2012; Strohle et al., 2023)**.

3 MATERIALS AND METHODS

The analysis is based on a comparison of international and Kazakhstani experience in 3D construction, the examination of specific case studies, and the inclusion of data from interviews with developers and project managers of 3D-printed construction projects. In addition, publications and scientific studies on biodegradable composites, energy-efficient poured concretes, and the principles of adaptive design were consulted.

4 RESULTS AND DISCUSSIONS

The Milestone project became the world's first commercial 3D-printed residential development **(Figure 1)**. It comprises five houses, each printed layer by layer from a concrete mix, with the final house intended to be fully assembled on site. The homes exhibit high energy efficiency, complex geometries and an aesthetic that would be impossible to achieve with conventional construction. Thanks to digital control of the construction process and optimized material use, the project achieved a significant reduction in its carbon footprint **(Souza, 2021; Walsh, 2018).**

Figure 1 - The world’s first residential project constructed from 3D-printed concrete, Eindhoven, Netherlands. Architects: Houben & Van Mierlo Architecten **(Souza, 2021)**.

In the context of a rapidly expanding housing shortage, particularly in developing countries, 3D printing is increasingly regarded as a tool for accelerated, adaptive and sustainable construction. A notable example is the Angolan innovator Power2Build, which aims to address the country's housing crisis - the company estimates a shortfall of up to 3 million dwellings, concentrated above all in the Luanda metropolitan area, one of the fastest-growing cities in Africa **(Figure 2)**, **(Le, T. T., et al., 2012)**.

Since 2022, Power2Build has been carrying out large-scale housing projects using large-format concrete 3D printing, deploying the Danish company COBOD’s BOD2 and BOD3 printer series. These units feature a modular design and are capable of constructing structures up to 15 m high, 15 m wide and 40 m long, with printing speeds of up to 500 mm/s. This approach substantially shortens construction schedules and reduces labor demands by minimizing the need for manual work in masonry and other preparatory on-site operations **(Frearson, A. 2018)**.

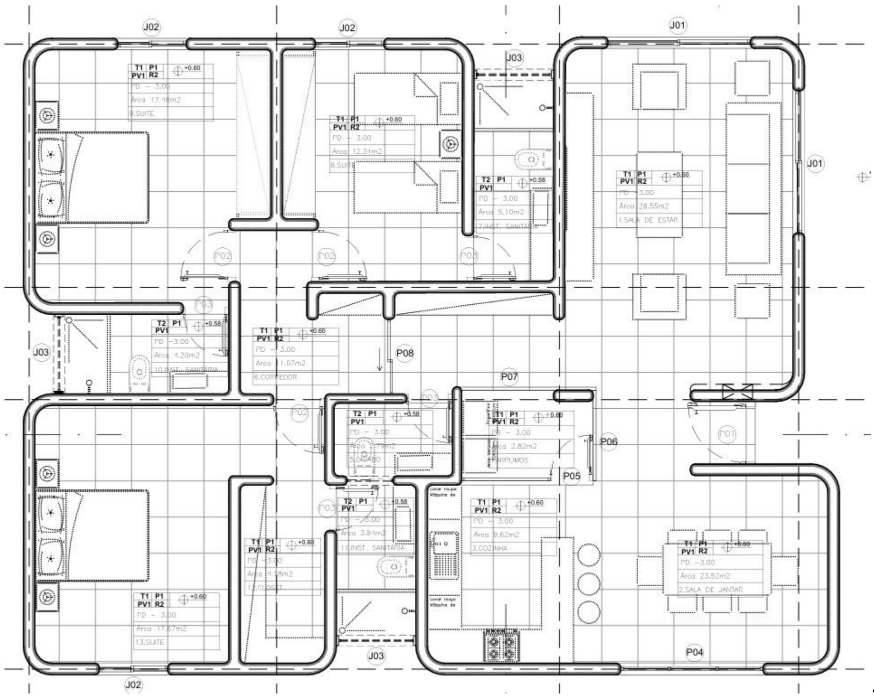

Figure 2 – Architectural plan of a residential duplex project implemented using 3D-printing technology in Angola. Architect: Ilídio Daio, Power2Build **(Frearson, A. 2018)**.

The printing process consists of three stages: modelling, preparation of a construction mix composed of cement, sand, crushed stone and other fillers, and the actual printing **(Figure 3)**. Specialized printers deliver high precision, geometric stability and strong interlayer bonding, in part through the use of continuous tangential material-deposition techniques **(Gosselin et al., 2016; Buswell et al., 2018)**.

The use of locally sourced materials helps reduce the carbon footprint and enhance the sustainability of projects. As part of its continued development, Power2Build plans to introduce clay- and earth-based mixes as well as modular construction solutions for social housing - an approach that makes this experience particularly relevant for resource-constrained regions **(Pineiro, A. 2025)**.

Figure 3 – Construction process of the residential duplex implemented using 3D-printing technology in Angola. Architect: Ilídio Daio, Power2Build **(Pineiro, A. 2025)**.

The Angolan experience demonstrates the potential of adaptive construction at the scale of mass housing, highlighting its relevance not only in high-tech contexts but also for social architecture. Such cases can be instructive when assessing the feasibility of implementing similar approaches in Kazakhstan's architectural practice, taking into account the country's climatic and infrastructural realities. BM Partners 3D Print executed the first residential building in Central Asia constructed with a COBOD BOD2 3D printer **(Figure 4)**. The project was adapted to seismic conditions of up to 7 on the Richter scale. The overall construction process took less than two months, while the wall printing itself lasted only five days. The company is also developing proprietary mix formulations that account for local climatic specifics.

Figure 4 – The first residential building in Central Asia constructed with a COBOD BOD2 3D printer. Architect/Builder: BM Partners 3D Print (authors' material).

Contemporary studies point to the promise of employing biodegradable composites-such as poly (lactic acid) (PLA), polyhydroxyalkanoates (PHAs) and polycaprolactone (PCL)-in architectural applications. These materials demonstrate favorable thermal and mechanical properties, align with environmental standards, and facilitate the integration of circular-economy principles. Their use enables the development of sustainable architectural solutions with minimal environmental impact **(Tkachenko T., et al., 2025)**.

Specialized dry building mixes, optimized for extrusion-based application, are used in construction 3D printing. Their formulation typically comprises a modified cementitious composite with functional additives, reinforcing fibers, and hydrophobizing and frost-resistant agents. The material's rheological properties-particularly its plasticity and setting rate-are of primary importance **(Колесникова, И. В., & Алгужина, Д. Р. 2021)**.

The adoption of 3D printing in Kazakhstan's architectural practice opens up opportunities to address the housing shortage, especially in remote and seismically active regions. The combination of digital design, novel construction materials and adaptive principles enables the creation of architecture that responds to contemporary challenges - from climatic threats to requirements for energy efficiency and local identity.

The architectural expressiveness afforded by construction 3D printing opens fundamentally new horizons in form-making. The technology allows the erection of spatial volumes with complex geometries while bypassing traditional constraints linked to formwork and manual labor. This expands the creative palette available to architects and designers, making it possible to realize previously unattainable compositional solutions with minimal time and material expenditures **(Strohle, M., et al., 2025)**.

Alongside this, the technology demonstrates high economic efficiency. Shorter construction schedules are accompanied by reduced operating costs through the use of multilayer assemblies with integrated thermal insulation and by optimizing the thermal performance of the building envelope. In some cases, final finishing stages can be partly omitted thanks to the high dimensional accuracy and surface uniformity achieved by printing.

Digitalization of the design and construction process is an integral component of the technology. The application of building information modeling (BIM), parametric design and CAM technologies enables a shift from empirical design to controlled, quantified and resource-optimized solutions. This is particularly relevant for Kazakhstan, where climatic diversity, territorial remoteness and the need for scalable approaches present pressing design challenges.

The digital model is developed in CAD environments (AutoCAD, ArchiCAD, Revit); thereafter the architectural data are adapted for printing in specialized CAM programs, such as Rhino with the Grasshopper module or the proprietary interfaces provided by 3D-printer manufacturers. The final stage is the generation of the machine control code (G-code), which the printing system executes to realize the object’s geometry in the chosen material.

5 CONCLUSIONS

The conducted analysis indicates that 3D printing in architecture has transitioned from an experimental technology to a practical tool capable of addressing sustainable-construction tasks. Accordingly, we arrive at the following conclusions:

1. 3D printing in architecture has moved out of the experimental domain and is now a practical instrument ready for deployment in construction.
2. International and Kazakhstani examples (the Milestone project, Power2Build, and the BM Partners 3D Print residential building in Almaty) confirm the technology’s potential for rapid and resource-efficient building delivery.
3. For Kazakhstan, the adoption of 3D printing is particularly relevant given seismicity, climatic heterogeneity and the need to modernize the housing stock.
4. The use of locally sourced materials, modified concretes and biodegradable composites, combined with digital design methods, enables the creation of adaptive and energy-efficient architectural solutions.
5. Form-making freedom, material savings and the integration of BIM/CAM systems reinforce the competitive advantages of 3D printing within the construction industry.

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