Technological Aspects of using 3D Printing Software in Construction

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Abstract: - The relevance of introducing additive technologies of 3D printing in construction is to decrease the technological cycle of construction, and minimize expenditure and material costs, while reducing the duration of the development planning process and execution, eliminating inaccuracies and defects, as well as optimizing and automate the process. The technological aspect of 3D printing lies in the optimal selection of parameters based on the created 3D model using effective software. The purpose of the study is to determine the quality indicators of bricks obtained by 3D printing from special concrete. The approach to investigating this matter is rooted in ascertaining the compressive strength of concrete through non-invasive testing techniques, gauging the density of concrete using measurement methods, and validating the efficacy of integrating 3D printing technologies in construction by the method of comparative analysis. The effectiveness of introducing additive technologies of 3D printing was proven drawing upon quality indicators of concrete obtained on a 3D printer which meets all the requirements necessary for its implementation in the construction field. The selected characteristics of concrete compressive strength are fundamental to the basics of selecting a brand of concrete to be utilized in construction. The selected software demonstrated the capacity to generate flawless 3D designs. The result of the study shows a significant reduction in the number of workers involved in the construction process by 38–45%, depending on the chosen method of using 3D printing; a decrease of construction time by 33–42% when printing individual elements, blocks used in production, and by 61−72% when using a printer directly on the construction site; reduction of raw materials costs by 14–28%; as well as reduction of construction downtime by 25%. The results obtained indicate the need to develop and enhance progressive additive technologies for 3D printing in construction.

Key Words: - 3D printing in construction, additive technologies, software setting parameters, print accuracy, slicer, concrete, concrete strength

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1 Introduction

The utilization of cutting-edge technologies, specialized software, and state-of-the-art equipment significantly streamlines the process of design and construction. Contemporary additive technologies represent a pivotal advancement in the field of construction. By establishing the prerequisites for the design of complex, formerly unattainable structures, be it in terms of their geometry, execution, or even scale, additive technologies have the potential to spark a revolution in the realm of technological advancement. The introduction of additive technologies for the creation of machine parts and designs will reduce production time, and the amount of equipment used, and enhance the quality and accuracy of parts. Among other benefits, the utilization of layer-by-layer construction will result in a reduction of material usage.

Consequently, not only will the cost of the component decrease, but the overall production expenses of the final product will also be minimized. Another significant advantage of introducing additive technologies is the artificial production of complex parts for which serial production is not of particular interest. The above aspects are relevant for the most costly and strategic industries. However, there exist several predicaments that necessitate attention. Namely, the legal underpinnings for 3D printing in construction must be established and appropriate structural materials selected to guarantee robustness, durability, ease of manufacturing, safety, and cost-effectiveness.

In this light, an important problem of establishing 3D printing on a permanent basis is the lack of available software and the necessary databases that will satisfy the reliable use of the software interface. The relevance of the study lies in the need to systematize programs for creating 3D models, establish their disadvantages and advantages, choose an algorithm for their use for certain purposes, create the ground for introducing 3D printing technologies in construction, enhancing the efficiency of their use, as well as developing a plan for their long-term development.

The purpose of the article is to determine the quality indicators of bricks, namely hardness, roughness of working surfaces, strength, compressive strength, elasticity, deviation of dimensional characteristics (sizes of the part, holes, protrusions, etc.) from tolerances, etc., obtained by the method of 3D printing from special concrete, as one of the principal characteristics of using materials in construction, analysis of world manufacturers' construction 3D printers in the context of their utilization directly in construction.

To achieve this purpose, the following tasks were addressed:

- conduct a comparative analysis of the pros and cons of additive 3D printing technologies;
- analyze 3D printers from manufacturers of world leaders;
- optimize the software settings to obtain the required geometric dimensions, strength parameters, and surface roughness of the printed 3D model;
- study the concrete compressive strength features and determination of concrete density while manufacturing bricks by 3D printing for use in construction;
- determine 3D printing effectiveness to be implemented in construction.

2 Literature Review

Additive manufacturing is a set of the latest technologies that use 3D printing methods to create structures, buildings, or structure's individual elements by printing solid layers by way of various materials intrusion by layer-by-layer overlay, [1], [2].

The inception and evolution of 3D printers in the process of creating architectural objects are attributed to numerous international corporations. with their standing out as preeminent pioneer leaders. The founder of three-dimensional printing is professor who in 2012 introduced the world's first printer. Numerous researchers and companies have devoted their scientific inquiry to this topical issue of improving 3D printing and implementing thereof in construction. A Chinese company WinSun gained leadership in this process, then such companies as the Italian architectural agency WASP, the company from the Netherlands Houben & Van Mierlo Architecten, from the USA Skidmore, Owings & Merrill and WATG'S Urban Architecture Studio, and many others continued to work, [3], [4].

The development of additive technologies for 3D printing is carried out in the following research areas:

– Development of new and introduction of existing additive 3D printing technologies in construction.

– Enhancement and elaboration of the relevant software that will create the prerequisites for implementing complex building models and structures as well as individual elements.

– Adaptation of regulatory documentation for the construction development areas.

– Improving the technical characteristics of 3D printers.

– Creation of universally reliable and technically applicable mixtures of materials for 3D printing.

– Improving the construction working conditions, reducing the number of the operation, decreasing the work time.

One of the key aspects of the finished structure quality is the concrete mixture composition, which is used to elaborate architectural projects and building structures, [1], [4], [5].

The classification of advanced 3D printing methods for construction draws upon numerous factors. Selection It is based on the criteria as follows, which form the classification ground, [6], [7], [8], [9], [10]:

1. According to the technology of creating objects:

- Extrusion-based technologies. This method involves the use of concretes based on cement, sand, polymers, and foam. Such a method is the most common one when it comes to 3D printing architectural objects in construction.
- Inkjet printing method (Binder Jetting). Within this method, a binding mixture is used that consists of polymers, and chemical compounds and is obtained by sintering.
- Electric arc growing using welding wire (WAAM, wire arc additive manufacturing).
- Technologies employing the creation of perpendicular formations by sliding, partial concreting of metal mesh, mesh framing, etc.
- Printing of individual elements, modules, and bricks (Modularity and Bricks).

2. According to the method of the 3D printer operation:

- The method of polar rotation of the printer around its axis when creating a layer-by-layer structure.
- Printers equipped with a versatile manipulator in various configurations.
- Delta printers.

3. According to the way different software is used:

- Software systems for creating 3D models.

This software allows designing and manipulating an object by providing the necessary instructions to the printer so as to create the physical object. Choosing the right software is critical to the success of the entire 3D printing process.

- Software for managing the printer itself.

This software allows managing the devices of any brand and better organizing the work processes. Such software and applications are designed to focus on print management and securely safeguard digital data in transit, while mobile solutions ensure the protection of sensitive printing operations.

All printers currently available are classified based on their dimensions and placement. Thus, there are printers working directly on the construction site, creating a layer-by-layer structure for the future construction (Figure 1(a)). The dimensions of such printers vary significantly depending on the scale of the construction site and can reach the dimensions of a powerful truck crane. The same printers that print small individual elements of a building in the factory are much smaller. That said, the elements in such printing are delivered to the construction site after creation, where they are assembled using conventional construction methods (Figure 1(b)), [5], [10], [11].

a) a printer working directly on the construction site

b) a printer for work in the factory to create individual items

Fig. 1: Types of Construction Printers

Neither of the above methods is perfect and has both pros and cons. However, using factory-run printers to create individual items avoids downtime relative to the work seasonality. The work is going on indoors, accumulating elements of the future building, which will be assembled firsthand. However, printers working directly on the construction site have the advantages of reducing the number of employees (only a printer operator is needed, and several assisting workers to create the mixture), and there are no assembly processes, leading to a reduction in risks and inaccuracies, [12], [13], [14].

Consequently, a thorough study of utilizing the construction 3D printers in the world practice showed significant advantages over traditional construction methods, [15], [16].

Advantages of 3D printing in construction:

1. Significant reduction in the duration of construction works.
2. Reducing the number of personnel involved in construction.
3. Workplace automation.

4. Reducing the cost of raw materials and supplies.

5. Reduce construction site time, and improve process quality and accuracy through programmatic control. Accordingly, cost reduction and avoidance of all possible risks.

6. Increasing safety and working conditions.

7. Raising awareness of environmental issues as while using 3D printing in construction, the formation of construction waste is significantly reduced. Furthermore, traditional construction waste is quite frequently used to create special building mixtures for 3D printers. In other words, there is a notable improvement in the environmental situation.

8. Reduction of time, materials, and costs for the construction of buildings with unique and complex architecture. Virtually any geometric shape became available. The duration of such construction is significantly reduced.

9. Exclusion from the workflow of delivering the necessary parts, the need to maintain warehouses, logistics and transport costs, etc.

10. Creation of diverse, complex, unique shapes, and reliefs, which until now were difficult to reproduce by traditional methods. The technology of 3D printing in construction can significantly reduce the entire process of creating forms and bas-reliefs, allowing cutting down on materials consumption. Consequently, it becomes possible to reliably reproduce the display of all geometric shapes and parameters.

That said, with a fairly impressive list of advantages, additive technologies also have a number of disadvantages, [13], [16], [17], [18]:

1. The cost of equipment and materials is quite high.

2. So far, it is not suitable for mass production but is available only for isolated cases. Currently, it remains unsuitable for widespread manufacturing and is solely accessible for limited instances.

3. The choice of materials is not wide enough, not all materials are reliable for use in construction. The selection of construction materials is limited in scope, and not all available options can be deemed entirely dependable.

4. Lack of trained specialists.

5. Failure of 3D printers when they are actively used.

6. To date, there are no uniform standards for the created building elements and structures obtained using 3D printers. Hence, achieving the requisite design feature and ensuring quality control becomes a challenging task All stages of preparing the 3D parts and 3D structures are not clearly elaborated.

7. Absence of a unified repository for implemented protocols.

8. Printers are slower than anticipated.

9. The need to equip the construction site compliant with the printer operation requirements. A smooth cover, rails parallelism, and the lack of any materials or tools on site ensure accuracy, printing reliability as well as obtaining structures of the required quality.

An important factor is the appropriate choice of software for 3-dimensional printers. Not only the aesthetic appeal and precision of replicating the model created depend on the exact reproduction of the intended design, the perfect calculation of all parameters, but primarily all the indicators of reliability, strength, and durability.

There are numerous CAD applications available for designing three-dimensional objects. It is crucial to select the appropriate software and meticulously configure all printer settings to achieve optimal results, to correctly reproduce the model in reality, [19], [20].

The utilization of 3D printing programs enables full automationautomating the process of creating structures, significantly reduce construction time, decrease waste, improve the situation of labor protection and the environment, reduce costs, and replace a large number of bulky equipment with high-tech ones. 3D printing devices are controlled using special software, which is based on the G-code.

The software is the link between the printer and the overall system operation. The software gives commands to the hardware of the computer system, allowing it to clearly assign tasks to the printer by translating program commands into a form that is recognized by the hardware.

Before starting a 3D printer, the following steps are to be addressed:

- Create a three-dimensional model in a special program.
- Set the necessary 3D printing parameters for the printer to get the desired result.

To create models, specialized design programs are used, such as FreeCAD, Autodesk ArtCAM, Paint 3D, ZBrush, KOMPAS-3D, and many others.

Conversion of the model into program code is carried out with the help of slicer programs, which translate the resulting highly discrete, polygonal 3D model into G-code for a 3D printer. The most common slicers are Cura, Kisslicer, Slic3r, and many others, [21].

The stages of 3D printing are as follows:

1. Creating a digital model.

This stage consists in creating a future three-dimensional object in a 3D editor or CAD program ("3D Studio Max", "AutoCAD", "Compass", "SolidWorks", etc.).

2. Export the 3D model to STL format.
3. G-Code Generation.
4. The STL file with the future object is processed by a special slicer program, which translates it into the control G-code.
5. Preparing the 3D printer for work.
6. Printing a 3D object.
7. Finishing of the object.

3 Materials and Methods

The operation of a 3D printer depends on its optimal software setup. Most of the indicators are set by the manufacturer. However, most of them can be customized to meet the specific requirements.

The most important indicator is the height of the printed layer. The thickness of the layer affects not only the speed (printing time) but also the quality. The number of layers adjusts the print speed on which the printer's runtime depends.

We also analyzed the work in the programs for ease of configuration, the possibility of quick learning, ease of control, ease of interface, and the accuracy of reproducing the created model in reality.

In construction, important indicators are the quality characteristics of the materials used. They must satisfy the requirements for their intended utilization purpose.

Verification of quality indicators, both finished structures and individual building elements, is carried out by visual inspection, determining the correspondence of geometric parameters and calculating important quality indicators, such as strength and density of concrete.

To determine the strength and density of concrete, bricks of the required size (100x100x100, 70x70x70, and 50x50x50) were printed using a 3D printer. To conduct a study on the strength and density of concrete, six samples of each size were produced. As the final result, the arithmetic mean of all measurements was taken.

The compressive strength of concrete (MPa) was established on previously obtained samples in accordance with the normative document, [22].

The obtained samples of printed bricks were subjected to destruction on a special laboratory press. At that, the bricks were laid on the press plate in such a way that the load was perpendicular to the layers of laying the concrete mixture in the structure.

The compressive strength of printed bricks was determined by dividing the destructive load by the cross-sectional area of the sample.

While performing the strength test, both the nature of the destruction and the structure of the concrete surface were observed.

Pressure strength is calculated by the formula:

$$Rm = (\alpha \cdot F \cdot kw)/A,$$

where F is the destructive load, N (kg/s);

A is the working cross-sectional area of the sample, cm2;

α is the cross-sectional width of the sample, mm;

Kw is the correction factor that takes into account the moisture content of concrete, we assume 1.

The density of concrete samples in kg/m3 was established in accordance with the normative document, [23], by weighing them and setting measurements in accordance with the weight and volume of the sample.

The roughness measurements of the brick surface were carried out using a profiler. Several measurements were simultaneously taken and the average value was determined, reducing the measurement error.

The characteristics of the obtained brick models were compared.

4 Results

The print settings are carried out using special software called a slicer. The choice of printing technology and software affects the final result. Specifications and output print speed alone cannot provide the required ideal. It is crucial to consider the complexity of setting up the software, the possibility of easy training of operators, the time of the process, the accuracy of the resulting structures in accordance with the established norms and models, the ease of changing materials, and so on. Table 1 shows the main characteristics of the different printing methods.

Table 2 displays the comparative characteristics of the prevalent 3D printing software utilized in construction.

Table 1. Comparison of Printing Characteristics and Printing Methods

Control parameters	3D printing method		
	FDM	SLA	SLS
Complexity of the preflight setup process	***	**	*
Preparing for launch	*	**	***
Replacement of printing materials	**	*	**
Print time, min	700 – 1800	100 – 520	2450
Post-print processing operations:			
– cleaning of the structure	Not required	**	*
– grinding of the structure	*	**	*

Table 2. Comparative Characteristics of Different Software

No.	3D printing software name	Function	Advantages	Disadvantages
		Software for making or designing a 3D model		
1	FreeCAD	software for creating and editing 3D models	free of charge; the ability to export models from other design programs; extensive database; user-friendly interface	knowledge of the Python programming language is required
2	Autodesk AutoCAD	creation of accurate 3D models with the ability to visualize the future design	has a built-in module for printing the model; allows working with 3D models, raster, and vector graphics; the ability to work on a collaborative project; visualization capability	a set of paid software
3	Autodesk Fusion 360	parametric modeling, assembly design, and 3D printing compatibility including modeling and analysis tools	the ability to integrate various tools and workflows into a single platform; cloud-based, making it easy to collaborate and share data between team members	challenging to get used to the interface and functionalities. requires a powerful computer for optimal performance
4	Paint 3D	standard software included in the Windows 10 operating system	allows creation simple 3D models	ease of use; ability to learn quickly; ease of operation; availability
5	ZBrush	used predominantly for artistic modeling of three-dimensional objects	powerful base for creating 3D models with accurate visualization	narrow profile, complexity of work, and study
6	COMPASS-3D	a set of universal software that allows you to work with both 3D models and objects, as well as with ordinary drawings	quick design of CA, ease of operation, ease of learning, user-friendly interface	a fairly low degree of sampling of the obtained models
		Slicers		
1	Cura	the simplest and most intuitive slicer	calculates the printing time, and the weight of the received part, has a layer-by-layer print visualization mode, and allows you to generate non-standard support templates	
2	Kisslicer	a cross-platform slicer	allows you to generate complex and reliable supports	high material consumption for the construction of supports
3	Slic3r	comes with the Repetier Host software, has a progressive three-dimensional cellular filling	frequent updates and configuration capabilities	challenging learning

To check the print quality of the structure, such characteristics as hardness, roughness of working surfaces, strength, compressive strength, elasticity, deviation of dimensional characteristics (dimensions of the part, holes, protrusions, etc.) relative to tolerances, compliance with the obtained angles, co-flatness, coaxiality, aesthetics of appearance are checked. To establish qualitative indicators, it is necessary to evaluate several characteristics. The most important are the characteristics of the accuracy of the obtained dimensions and the roughness of the part.

Surface roughness is a characteristic of unevenness that determines the deviation degree along the base length from theoretically smooth surfaces of a given geometric shape. This parameter has the strongest influence on operational characteristics of the products as well as parts and assemblies of various purposes. The surface roughness plays a crucial role in determining the longevity of the operational efficiency of the mating components. At the same time, it should be noted that the durability of the components is contingent on this parameter. The degradation of components is attributed to surface irregularities. The surface roughness plays a pivotal role in connections that meet the requirements of density and tightness.

Complex interaction at all stages of 3D printing gives the desired result. In order for the printer to work best and produce the desired result, you need high-quality software and qualified configuration. The entered parameters with the correct calibration will give the desired result.

As studies show, perfect surfaces cannot be obtained. Because the layer-by-layer application of the material leaves some irregularities, especially at the ends, leaving furrows and small protrusions. Setting parameters in 3D printing programs is very important, the accuracy of the setting depends on the software and on the skills of the operator. Table 3 shows the print quality indicators depending on changes in parameters.

The examination of the acquired data reveals that a number of factors impact the quality of the part: printing speed, the accuracy of moving the nozzle of a 3D printer, the thickness of the printed layer, as well as a combination of these parameters. Printing speed affects the quality of layer application, their hardening rate, and better adhesion within the layer itself and between the previous and next layer. Accordingly, an increase in the layer thickness and overlap reduces the corresponding subsidence of the material from which the part or structure is printed.

However, an increase in speed and a decrease in the thickness of the layer of the part receive greater dimensional accuracy. Reducing print speed and layer thickness at the same time reduces accuracy. Increasing the layer thickness at low print speeds will have a positive effect on the accuracy of the resulting size.

Table 3. Software Configuration Results

Experiment No.	Customizable parameters				Results		
	Printin speed, mm/s	Layer thickness, cm	Floor thickness, mm	Accuracy of 3D printer nozzle movement	Brick surface roughness, µm	Accuracy of the obtained dimensions (±deviation of dimensions from the specified dimensions), mm	Brick strength, MPa
1	30	2	1	0,2	8,65	-0,29; -0,129; +0,25	27,64
2	30	3	2	0,3	9,28	+0,28; +0,34; -0,27	29,75
3	30	5	3	0,4	8,74	-0,32; -0,25; +0,24	35,02
4	40	2	1	0,2	7,32	-0,32; +0,22; -0,28	28,95
5	40	3	2	0,3	6,42	+0,29; +0,22; -0,28	31,21
6	40	5	3	0,4	5,89	+0,29; +0,32; -0,23	36,54
7	50	2	1	0,2	4,98	+0,24; +0,25; +0,29	27,59
8	50	3	2	0,3	5,65	-0,29; -0,19; +0,24	33,14
9	50	5	3	0,4	4,72	-0,31; +0,25; -0,28	34,25
10	60	2	1	0,2	4,61	+0,2; -0,18; +0,21	26,16
11	60	3	2	0,3	3,25	+0,26; +0,22; -0,19	29,65
12	60	5	3	0,4	2,85	+0,32; -0,29; -0,33	34,85

Table 4. Results of the Studying Concrete Samples (author's findings)

Sample No.	Sample size, mm	Sample weight, g	The cross-sectional width of the sample, α, cm	Working cross-sectional area of sample A, cm^2	Sample volume V, cm^3	Density, ρ, g/cm^3	Destructive load F, kN	Compressive strength R_m, MPa
1	100x100x100	1958	10.05	100.1	1015.1	1.93	348.23	36.52
2	70x70x70	723	7.1	48.48	357.9	2.02	198.97	29.13
3	50x50x50	253	5.01	25.1	125.75	2.01	147.55	29.45

Table 5. Characteristics of the Materials' Parameters Used for 3D Printers from Different Manufacturers

No.	The company that developed the 3D printer	Material that is needed for this 3D printer	Compressive strength, MPa	Material density, g/cm^3
1	WinSun (China)	A mixture of cement and sand using construction waste and adding additives	35.0	2200
2	Contour Crafting Corporation (USA)	High-strength concrete with the addition of kaolin	More than 30	2350
3	Bet Abram (Slovenia)	Shotcrete concrete with sand and gravel aggregate	-	2300
4	Loungborough University (UK)	Cement-based fine-grained concrete	110.0	2250
5	Cy Be Construction (Netherlands)	A mixture of cement and sand with the addition of mineral additives	45.0	2250

Table 6. Advantages and Disadvantages of 3D Printers from Different Manufacturers

No.	The company that developed the 3D printer	Advantages of 3D printers in 3D printing in construction	Disadvantages of 3D printers in 3D printing in construction.
1	WinSun (China)	Use of construction waste, improvement of the environmental situation, economic value	The need for a perfectly equipped construction site, large space, and significant maintenance by personnel.
2	Contour Crafting Corporation (USA)	It is possible to choose the reinforcement method	Requires formwork. Imperfect surface of the resulting structures, which requires additional processing.
3	Bet Abram (Slovenia)	The ability to use various chemical additives, which allows thecreation of materials with varied properties for different purposes	Imperfect surface of the resulting structures, which requires additional processing. Uneven formwork.
4	Loughborough University (UK)	Creates high-strength structures. It is possible to use various reinforcing structures	Imperfect surface of the resulting structures, which requires additional processing. Creating an uneven vertical surface.
5	Cy Be Construction (Netherlands)	Creates high-strength structures. It is possible to use various reinforcing structures	Imperfect surface of the resulting structures, which requires additional processing. Creating an uneven vertical surface.

For construction, not only the printing process in itself is important, but also obtaining reliable, durable, strong structures. Construction machinery and equipment serve as the foundation of every technological process involved in erecting buildings and structures. In fact, a plethora of machines are utilized throughout the construction process, but it is the use of 3D printing that will allow discarding all these machines and replacing them only with a 3D construction printer.

The cornerstone of construction is rooted in the materials employed for erecting edifices. These components must satisfy all fundamental functions inherent to the building.

The results of the study of compressive strength and density of concrete samples produced by 3D printing, depending on their dimensions, are shown in Table 4.

According to Table 4, the compressive strength of concretes obtained from special mixtures for 3D printers, regardless of the edge size, refers to the normative data and also has a characteristic nature of destruction under a given load. At the same time, the samples' strength gradually increases with the sample's edge reduction in size. The above trend is typical for concrete.

The external structure of concrete has some porosity and increased surface roughness. Bricks made of such concrete require further processing, leveling, and grinding, which must solely be executed with the involvement of an individual. It is imperative to select the right concrete composition formulation that would meet all the construction needs. Consequently, this raises the question of further research in this direction, the introduction of innovative processing methods, and the formulation of new problems that need to be addressed. Still, all this unequivocally testifies that this direction is very relevant and promising.

The principle of 3D printer operation is to feed the concrete-based material obtained in advance with the addition of appropriate mineral, chemical, and reinforcing additives to a special nozzle, namely an extruder. The addition of auxiliary substances is based on the need to provide the building material with the requisite performance characteristics, it provides the basis for creating a future building structure Table 5 shows an analysis of all materials for the corresponding 3D printers used in modern construction. Table 6 shows the advantages and disadvantages of these construction industrial 3D printers from different companies.

The introduction of 3D printing technology in construction based on the experience of world leaders yielded the results as follows (Figure 2):

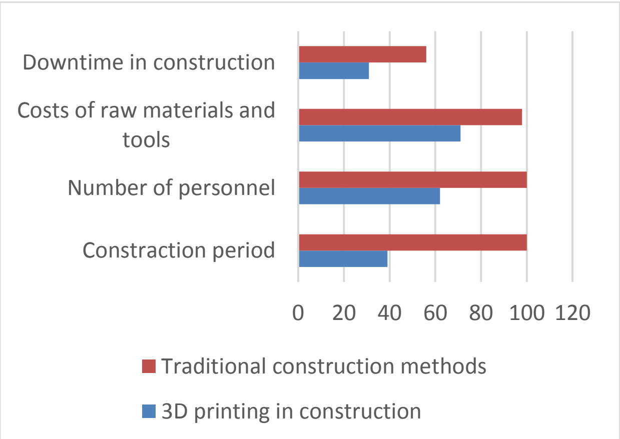

Fig. 2: Effectiveness of 3D Printing Technologies in Construction (author's findings)

1. As can be seen from the figure, there is a reduction in construction time by 33–42% when printing individual elements, and blocks used in production, and by 61–72% when using a printer directly on the construction site.
2. The number of personnel required for construction using 3D printing decreased. The involvement of workers in construction is needed only for machine maintenance, communications, etc. The number of employees decreased by 38%.
3. Raw material costs have been reduced by 27%.
4. Construction downtime decreased by 25%.

The data obtained suggest that in the near future, there will be a breakthrough in the use of additive 3D printing technologies in construction. Thus, it can be seen that the efficiency of three-dimensional printing is expedient and promising. Obviously, 3D printing technology is aimed at achieving excellence in constructing durable buildings, resulting in material conservation. reduces the need for large-sized lifting equipment, gives grounds for preserving the environmental situation, makes it possible to keep construction sites orderly, and has limited space for construction.

5 Discussion

An examination of the outcomes concerning the durability and compactness of concrete blocks derived from 3D printing enables determining the viability of employing concrete to build a particular structure. Studying the durability and compactness outcomes of 3D-printed concrete blocks enables the assessment of the feasibility of utilizing concrete for the construction of a specific structure. The selection of material for printing depends on the structure size, the loads during its operation, and the obtained parts' strength. The specifications for components, their surfaces, and their quality attributes are established based on the functional purpose of the product.

Due to the absence of standards for 3D-printed building materials, such studies are important and relevant in view of the norms for traditional technologies. On their basis, it will be necessary to establish the brand and class of concrete, elaborate regulations and standards.

The results obtained will allow in the near future to move from theory to practice and introduce such an effective construction method as 3D printing technology and make the construction process fast, efficient and modern.

Intelligent technologies are being actively integrated into production processes worldwide. The use of many digital methods has shown promising results. Therefore, many strive not only to introduce advanced 3D printing technologies instead of traditional construction methods but also to provide the necessary software modeling and specialist training in this field.

To tackle numerous production issues, the experience and practice of many companies working in the same direction are involved, [7], [10], [23], [24], [25], [26], [27]. Particular attention was paid to the abovementioned issues by architects, design engineers, designers, and representatives of well-known leading companies. Furthermore, apart from these well-known specialists in the field of using 3D printers, scientists from all over the world took part in the research process. Those renowned researchers confirmed the effectiveness and relevance of the innovative approach in laboratory conditions. It is their research that provides the basis for further development and implementation of additive technologies in reality.

Thus, Shanghai WinSun is a renowned leader in this market. Its experience and commitment to improvement have created a number of devices that allow not only to print individual elements, but also to work directly on the construction site, creating not only the base, frame, and structure, but also complex majestic elements of classic façade ornament at a relatively small cost of all types of resources, [28]. This direction of the company will make it possible to automate and adapt tasks in the field of construction at the global level, [29], [30], [31], [32], [33], [34].

Therefore, analysis of universal needs, licensing, integration, and features of the association will help determine the right solution to bring the implemented additive construction to an effective level of development.

6 Conclusion

The article discusses additive technologies for the creation of complex previously inaccessible structures, structures, and buildings, both in geometry and in the execution method. Analysis of the major aspects of three-dimensional printing in construction makes it possible to build a plan to improve the efficiency of introducing and distributing additive technologies and predict promising directions for the development of 3D printing. The conducted study analyzed the capabilities of available printers in the global market, their advantages and disadvantages, substantiating the prospects for actual implementation. Nevertheless, the problem of selecting either model remains a pressing issue. Moreover, the cost of such equipment is too high.

A comprehensive analysis of the existing software was carried out to create high-quality three-dimensional models for further reproduction into reality. A comparative characteristic of different programs and slicers was provided. The results of printing the model were shown depending on the software settings.

The choice of the printing material is an equally significant consideration. The characteristics of concretes produced by various manufacturers differ both in their composition and in their properties. This shows the need for further research in this direction. Analyses were carried out to determine the bricks' quality indicators obtained using 3D printing from special concrete. Notably, studies on the compressive strength of concretes obtained from special mixtures for 3D printers, regardless of the edges' size, belong to the normative data and have a characteristic nature of destruction under this type of load. At the same time, the samples' strength gradually increases with the sample's edge reduction in size.

The impact of surface roughness on the operational efficiency of components is thoroughly analyzed. It was determined that for the production of high-quality and reliable products, it is necessary to conduct a mandatory control of the surface roughness. The necessity to quantify the surface roughness in order to adhere to the specified parameters is crucial for ensuring the high quality and consistent production of parts and products. This process also aids in preventing the launch of items that fail to meet the specified requirements.

Since the quality of the part is influenced by a multitude of factors.: printing speed, the accuracy of movement of the nozzle of the 3D printer, the thickness of the printed layer, as well as a combination of these parameters, it is imperative to meticulously regulate them, as well as carry out further examinations on the influence on the ultimate quality of products.

The effectiveness of implementing 3D printing in construction shows a reduction in construction time by 33–42% when printing individual elements and blocks used in production, and by 61–72% when using a printer directly on the construction site. Moreover, the number of workers involved in production decreased by 38%; the raw material costs were reduced by 27%; Production downtime was reduced by 25% overall. That being said, the efficiency of three-dimensional printing is expedient and productive.

References:

[1] M. D'Angelo, Edg Wants to Resurrect Architectural Ornament Through 3D Printing. Architect. 2019, [Online]. https://www.architectmagazine.com/technology/edg-wants-to-resurrect-architectural-ornament-through-3d-printing_o (Accessed Date: February 12, 2024).

[2] R. Bates, S. Carlisle, B. Faircloth and R. Welch, Quantifying the Embodied Environmental Impact of Building Materials During Design: A Building Information Modeling Based Methodology, [Online]. https://www.semanticscholar.org/paper/Quantifying-the-Embodied-Environmental-Impact-of-A-Bates-Carlisle/59243637ec1fd1bac0f56515d476141d76c890a3 (Accessed Date: February 12, 2024).

[3] M. D. Bovea, V. Ibáñez-Forés and I. Agustí-Juan, 7- Environmental product declaration (EPD) labelling of construction and building materials, In F. Pacheco-Torgal, L.F. Cabeza, J. Labrincha & A. de Magalhães, eds. *Eco-efficient Construction and Building Materials*. Woodhead Publishing, 2014, pp. 125-150. https://doi.org/10.1533/9780857097729.1.125

[4] Gh. S. Hamidreza, J. Corker and M. Fan, Additive manufacturing technology and its implementation in construction as an ecoinnovative solution. *Automation in Construction*, Vol. 93, pp. 1–11, 2018, https://doi.org/10.1016/j.autcon.2018.05.005.

[5] S. Ivanov-Kostetskyi, I. Gumennyk and I. Voronkova, Innovative trends in architecture – Creating full-scape buildings with the 3D print technology. *IOP Conference Series: Materials Science and Engineering*. Vol. 1203, paper 022099, 2021, https://doi.org/10.1088/1757-899X/1203/2/022099.

[6] M. Savytskyi, O. Konoplianik, S. Unchik, S. Dukat and A. Savytskyi, (Eds.), *Sustainable Housing and Human Settlement: monograph*, Dnipro: SHEE "Prydniprovska State Academy of Civil Engineering and Architecture"; Bratislava: Slovak University of Technology, 2018. https://doi.org/10.15802/978-966-323-182-2.

[7] C. Gosselin, R. Duballet, Ph. Roux, J. Dirrenberger and P. Morel, Largescale 3D printing of ultra-high performance concrete—a new processing route for architects and builders. *Materials and Design*, Vol. 100, pp. 102–109, 2016. https://doi.org/10.1016/j.matdes.2016.03.097.

[8] R. Duballet, O. Baverel and J. Dirrenberger, Classification of building systems for concrete 3D printing. *Automation in Construction*, Vol. 83, pp. 247–258, 2017, https://doi.org/10.1016/j.autcon.2017.08.018.

[9] A. Perrot, D. Rangeard and A. Pierre, Structural built-up of cement-based materials used for 3D printing extrusion techniques. *Materials and Structures*, Vol. 49, pp. 1213–1220, 2016. https://doi.org/10.1617/s11527-015-0571-0.

[10] M. V. Savytskyi, S. V. Shatov and O. A. Ozhyshchenko, 3D-printing of build objects. *Bulletin of the Dnipro State Academy of Construction and Architecture*, Vol. 3, pp. 8–26, 2016, [Online]. http://visnyk.pgasa.dp.ua/article/view/66231 (Accessed Date: February 12, 2024).

[11] P. Shakor, J. Sanjayan, A. Nazari and S. Nejadi, Modifed 3D printed powder to cement-based material and mechanical properties of cement scafold used in 3D printing. *Construction and Building Materials*, Vol. 138, pp. 398–409, 2017. https://doi.org/10.1016/j.conbuildmat.2017.02.037.

[12] B. Khoshnevis, Automated construction by contour crafting-related robotics and information technologies. *Automation in Construction*, Vol.13, No.1, pp. 5–19, 2004, https://doi.org/10.1016/j.autcon.2003.08.012.

[13] X. Wang, M. Jiang, Z. Zhou, J. Gou and D. Hui, 3D printing of polymer matrix composites: A review and prospective. *Composites Part B: Engineering*, Vol. 110, pp. 442–458, 2017. https://doi.org/10.1016/j.compositesb.2016.11.034.

[14] Ye. L. Zaiats, T. S. Kravchunovska, V. V. Kovalov and O. V. Kirnos, Risk level assessment while organizational-managerial decision making in the condition of dynamic external environment. *Scientific Bulletin of National Mining University*, Vol. 2, pp. 123-129, 2018, https://doi.org/10.29202/nvngu/2018-2/24.

[15] U. Marushchak, M. Sanytsky and Y. Olevych, Effects of elevated temperatures on the properties of nanomodified rapid hardening concretes. *MATEC Web of Conference*, Vol. 116, paper 01008, 2017. https://doi.org/10.1051/matecconf/201711601008.

[16] J. Stansbury and M. Idacavage, 3D printing with polymers: Challenges among expanding options and opportunities. *Dental Materials*, Vol. 32, pp. 54–64, 2016. https://doi.org/10.1016/j.dental.2015.09.018.

[17] P. O'Regan, P. Prickett, R. Setchi, G. Hankins and N. Jones, Metal based additive layer manufacturing: variations, correlations and process control. *Procedia Computer Science*, Vol. 96, pp. 216-224, 2016, https://doi.org/10.1016/j.procs.2016.08.134.

[18] A. Armillotta, Assessment of surface quality on textured FDM prototypes, Rapid Prototyping Journal, Vol. 12, No. 1, 35–41, 2006. http://dx.doi.org/10.1108/13552540610637255.

[19] S. Kadiri, V. Dukovski, K. Jakupi and G. Hodolli, Optimizing 3D-Printed workpieces for radiotherapy application: Modelling the CT Number and print time. *Biomedical Physics & Engineering Express*, Vol. 10, No. 2, pp. 18–21, 2024, https://doi.org/10.1088/2057-1976/ad1d0b.

[20] F. Bos, Z. Ahmed, E. Justinov and T. Salet, Experimental exploration of metal cable as reinforcement in 3D printed concrete. *Materials*, Vol. 10, No. 11, paper 1314, 2017. https://doi.org/10.3390/ma10111314.

[21] K. F. Garff, M. Short and M. Norfolk, Very high power ultrasonic additive manufacturing (vhpuam) for advanced materials. In *Proceedings of the Solid Freeform Fabrication Simposium*, Austin, Texas, USA, 2010, pp. 82-89, [Online]. https://www.researchgate.net/publication/267859331_Very_high_power_ultrasonic_additive_manufacturing_VHP_UAM_for_advanced_materials (Accessed Date: February 12, 2024).

[22] D. S. Thomas, and S. W. Gilbert, Costs and cost effectiveness of additive manufacturing. *NIST Special Publication 1176*. NIST, USA, 2014, http://dx.doi.org/10.6028/NIST.SP.1176.

[23] D. Delgado, P. Clayton, W. J. O'Brien, C. Seepersad, M. Juenger, R. Ferron and S. Salamone, Applications of additive manufacturing in the construction industry: A prospective review. *In 2017 Proceedings of the 34rd ISARC, The International Association for Automation and Robotics in Construction*, Taipei, Taiwan, 2017, pp. 246-253. https://doi.org/10.22260/ISARC2017/0033.

[24] M. Kreiger and J. M. Pearce, Environmental life cycle analysis of distributed three-dimensional printing and conventional manufacturing of polymer products. *ACS Sustainable Chemistry & Engineering*, 2013, Vol. 1, No. 12, pp. 1511–1519, 2013. https://doi.org/10.1021/sc400093k.

[25] M. Yossef and A. Chen, Applicability and limitations of 3D printing for civil structures. In: *Proceedings of the 2015 Conference on Autonomous and Robotic Construction of Infrastructure*. Ames, USA, 2015, pp. 237–246, [Online]. https://www.researchgate.net/publication/277665549 (Accessed Date: February 12, 2024).

[26] S. O. Ivanov-Kosteckyy, I. Gumennyk and I. Voronkova, Ways of applying 3D printing technologies in the creation of modern architectural objects. *Bulletin of the National University "Lviv Polytechnic"*, Vol. 4, No. 1, pp. 54-64, 2022, https://doi.org/10.23939/sa2022.01.054.

[27] J. Lee, J. An and C. Kai Chua, Fundamentals and applications of 3D printing for novel materials. *Applied Materials Today*, Vol. 7, pp. 120–133, 2017. https://doi.org/10.1016/j.apmt.2017.02.004.

[28] K. Hossain, D. Ametrano and M. Lachemi, Bond Strength of GFRP Bars in Ultra-High Strength Concrete Using RILEM Beam Tests. *Journal of Building Engineering*, Vol. 26, No. 3, pp. 69–79, 2017. https://doi.org/10.1016/j.jobe.2017.02.005.

[29] M. Wei, W. Li and J. Yang, State-of-the-art of 3D printing technology of cementitious-An emerging technique for construction. *Science China Technological Sciences*, Vol. 61, pp. 475–495, 2018. https://doi.org/10.1007/s11431-016-9077-7.

[30] A. Manjunath, V. Anandakrishnan, S. Ramachandra and K. Parthiban, Experimental investigations on the effect of pre-positioned wire electron beam additive manufacturing process parameters on the layer geometry of titanium 6Al4V. *Materials Today: Proceedings*, Vol. 21, pp. 766-772, 2019, https://doi.org/10.1016/j.matpr.2019.06.755.

[31] V. Dhinakaran, J. Ajith, A. F. Y. Fahmidha, T. Jagadeesha, T. Sathish and B. Stalin, Wire Arc Additive Manufacturing (WAAM) process of nickel based superalloys – A review. *Materials Today: Proceedings*, Vol. 21, pp. 920-925, 2020, https://doi.org/10.1016/j.matpr.2019.08.159.

[32] A. Mardani-Aghabaglou, M. Tuyan, G. Yılmaz, Ö. Arıöz and K. Ramyar, Effect of different types of superplasticizer on fresh, rheological and strength properties of self-consolidating concrete. *Construction and Building Materials*, Vol. 47, pp. 1020–1025, 2013. https://doi.org/10.1016/j.conbuildmat.2013.05.105.

[33] K. Salonitis, Design for additive manufacturing based on the axiomatic design method. *International Journal of Advanced Manufacturing Technology*, Vol. 87, No. 1, pp. 989–996, 2016. https://doi.org/10.1007/s00170-016-8540-5.

[34] I. Gibson, D. Rosen, B. Stucker, Design for additive manufacturing. In *Additive Manufacturing Technologies*. New York, NY: Springer, 2015, pp. 399-435. https://doi.org/10.1007/978-1-4939-2113-3_17.

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