Innovative Trends in Architecture – Creating Full-Scape Buildings with the 3D Print Technology

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Abstract. Contemporary innovative 3D technologies and machinery to apply them in the 21st century have been dynamically developing and cover increasingly more aspects in the area of architecture when making buildings and structures for various purposes. In the recent years, in various parts of the world much focus has been made on the kind of 3D technologies such as printing real-life architectural structures on printers using the method of phased production by the digital three-dimensional model designed in advance for the architectural project. The paper considers various technologies and technical means, their advantages and flaws, and analyzes key areas of applying 3D printers in the process of implementing various architectural structures. The prospects are identified for the development of the highly efficient technology to construct buildings and structures. The functioning principles of 3D printers are described. We covered the developments of construction and architectural organizations in making structures with the help of 3D print. Key challenges have been identified in the practical application of 3D print when building the architectural structures; the ways to improve the technology in the future are presented. The authors analyzed the available technological solutions for 3D print in the process of constructing real architectural structures; presented the relevant data on technical parameters of the contemporary three-dimensional printers; the problems for the development of the technology have been conceptualized, as well as the choice of optimal materials and engineering structures with regard for peculiarities of selected methods of layer-wise extrusion or making buildings parts with their further assembling into the final structure. The paper presents a summary of basic notions in the 3D print area; it mentions key software programs that could help implement all stages of the architectural structures making process when constructing them. The authors suggested a list of traditional construction materials to create architectural projects such as mineral heavy weight concrete with the polymer disperse fiber and chemical additives to regulate the terms for hardening astringency, and the promising other materials to produce buildings such as structural glass, various kinds of plastics, ceramic alloys (produced through selective laser sintering), and salt as a basic material to make complex restoration works in the reconstruction process. The outcome of the undertaken theoretical and applied research is presented by the authors in the findings concluding about key benefits from using 3D printers in creating real architectural facilities for various functions, and the choice of an optimal 3D print method on the specific brand of manufacturing machinery with the most efficient software. The authors identified the application areas of the most optimal, economically and structurally justified construction materials fitting the selected technology to build an architectural structure on a 3D printer. The approach can help create relatively inexpensive, aesthetically and functionally interesting architectural facilities for various purposes. In the process of their construction, they entail minimum costs in terms of labor and material resources. It offers broad perspectives to apply 3D printers in the world’s architectural practices.
1. Introduction

Contemporary innovative 3D technologies and machinery for their application have been dynamically evolving in the 21st century. They have been covering increasingly more aspects in architecture when making buildings and structures for various purposes. In the recent years, in various parts of the world, much focus has been made on the kind of 3D technologies such as printing real-size architectural structures on printers with the method of phased production under the digital three-dimensional model designed in advance for the architectural project. The paper considers different technologies and technical means, their advantages and disadvantages, as well as key areas for the application of 3D printers in the process of building architectural objects. The development prospects have been analyzed for the extremely efficient technology to build buildings and structures.

The use of the 3D technology is a new chapter in global architectural practices of the late 20th – early 21st centuries [1]. At the same time, the three-dimensional print is related to an additive production. In other words, the technology helps create architectural objects by phased application of construction material coats according to the previously set path. In the process of fast production, the architectural objects produced with the help of modern 3D printers are available either in the ready-to-use form, or as separate elements of prefabricated ready-to-operate forms, to be later assembled under the designed pattern as part of the construction site.

The most widely used technologies in 3D print are the following three methods [2]:
- sintering method (selective laser sintering) (SLS);
- a method of laser stereolithography (SLA);
- a method of multilayer extrusion (LOM).

Key objectives of the paper are to analyze key trends, to explore the shortcomings and advantages of the selected 3D print technologies, and to identify the high-potential areas for the implementation of various types of architectural facilities produced on the new generation three-dimensional printers.

2. Technological features of 3D printing use in the architectural objects creation

Science has been advancing, and new technologies are fast progressing in today’s architectural practices. The overall objective in the development of new technological solutions for building architectural objects is to reduce the construction term, to save on labor and workforce costs, to increase the operating lifetime of buildings, and eventually, to save financial resources for the economic benefit. At the same time, major areas of interest in new digital technologies cover an environment protection focus and safe working conditions in the process of building modern architectural facilities.

The principle of the selected sintering method in the 3D print can be described as follows: a 3D printer uses a concentrated laser ray or UV rays to melt the working mixture of a common construction sand (siliceous or spar sand). The method was authored by an engineer Markus Kayser who patented the authentic industrial machinery for 3D print through the selective sintering method. The technological machinery allows to sinter the construction material to further layer it under the programmed pattern into the structure’s elements; when in the process of melt solidification, they assume the required shape designed for the operations of the future building’s section.

The application of the second 3D print method on industrial printers for architectural objects, i.e. the laser stereolithography, requires to have the special laser equipment with a container (known as a vat) and a special print bed. The special liquid mixture (usually, polymer composite mixture) is sintered with a laser equipment with the method of phased movement of laser ray according to the pre-programmed path. The specificity of the phased laser stereolithography method is in the fact that the polymer mixture shall have the photopolymerization property under the active laser radiation. Then, the working samples of the structure’s elements 3D-printed on the relevant printers class are lowered a step further on a bed into the vat with the photopolymer composite to shift to the stage of making the next layer of the structure’s next element. Sometimes, the 3D method is referred to as the spray
coating method. The leading research institution for this method in the process of 3D print is the Institute of Advanced Architecture of Catalonia (IAAC) and a firm MonoPite (UK). With the help of composite fusion, they make objects known as Stone Spray Robot. The author of the technique used in the 3D print process with the method of component-based fusion of elements produced with the laser stereolithography method, layerwise, is a researcher Enrico Dini. He patented the technology as a D-Shape [3]. The specificity of selective sintering and laser stereolithography methods applied in 3D printers on architectural sites is their high environmental friendliness. In fact, in the process of their application in 3D print, they use solar power, and the major working mixture for production is sand or a polymer composite, the highly safe construction materials.

The third 3D print method for architectural structures, the so-called multilayer extrusion method, is the most widespread option for 3D printers in the actual production of buildings and structures. The operational concept is based on the method when the extruder (working nozzle) of the industrial 3D printer is receiving the quick-setting fine-graded mixture of heavy concrete, with the respective mineral, chemical, and reinforcing additives. The additives included into the concrete mixture shall provide for all the necessary project design operational features of the future structure in the architectural facility. The 3D print technology was first suggested in 2012 by a professor Behrokh Khoshnevis from South California University, when he presented his idea to make a giant 3D printer on construction site similar in structure to an overhead crane [4]. A Chinese Win Sun company has made the highest progress so far in using the multilayered extrusion method in 3D print. In 2014, they started mass production of architectural facilities made of a mixture of construction debris, fine-grade concrete, and special additives. In fact, it was the first experience of creating low-cost housing as architectural objects for serial mass construction [5].

To a large extent, the prevalence of the above 3D printing methods depends on the printers used to make the real-life architectural objects. The most common design solutions for 3D printers are options in the form of a bridge crane and a manipulator arm [6]. Tables 1 and 2 list basic technical parameters leading producers, as well as advantages and disadvantages in the area of application of 3D printers available today and used in architectural practices in different countries in the world. The 3D printing technologies presented in this analysis are used by leading firms currently active in the construction of architectural objects with the 3D print method. The first option of employing the technology is when a 3D printer is located directly on the construction site, and the building process is usually about the method of multilayered coating of a concrete mixture on a mineral binder, along the path pre-programmed by the design. In the second case, the dimensional elements of the building’s sections are printed on a 3D printer in industrial factory environment. Later, the ready-made building fragments are transported to the construction site to be further assembled in a conventional way, on the ground. Moreover, the speed of producing a finished architectural object on a 3D printer is impressive. The average speed is up to 24 hours. In other words, the finished 3D printed building can be delivered in a day.

In the current situation, 3D print usually produces a support frame of a building or a structure (walls, inter-floor covering, foundations, stair flights and landings, ceiling and roofing elements). Presently, 3D printers are not able to fully replace the labor of all building trades. However, the fact will become the reality in the near future. Besides, the three-dimensional printing technology can help dispose of certain monotony in standard housing construction in urban residential areas, as the computer modelling method can largely contribute to the variety of architectural distinctness of buildings that could be assembled from sets of finished elements pre-fabricated on the industrial 3D printers.

The analysis of the presented 3D printing technologies and the list of firms using the 3D printers in the process of producing buildings and structures shows that the most demanded materials include the light concrete fine-grade and cement-sand concrete mixtures. In addition, we can mention the use of recycled materials from the building processes (recycling) and the use of special shuttering systems based on polymer compositions. At the same time, there is a high variety in strength engineering
structures profiles of the support frame produced with the industrial 3D printers help. The fact can largely contribute to the extended application of three-dimensional printing in making wider range architectural objects and versatile functions. Another advantage of the 3D printing can be in the capability of 3D printers to reproduce any architectural ideas. A famous Dutch architect Janjaap Ruijssenarrs managed to create an unusual configuration on a 3D printer: a Landscape House shaped as a Moebius strip.

**Table 1.** Analysis of technical specifications in the process of a 3D print of buildings in modern architectural practices

| No | A 3D printer developing company | Materials used in the architectural object | Material durability parameters, MPa | Density of material, kg/m³ |
|----|---------------------------------|--------------------------------------------|-----------------------------------|--------------------------|
| 1. | WinSun (China)                  | Cement-sand mixture, construction debris upon recycling, with added shavings | 8.2 35.0 | 2200 |
| 2. | Contour Crafting Corporation (USA) | High-strength cement mixture or glass fiber reinforced concrete with kaolin additive | – over 30.0 | 2350 |
| 3. | Bet Abram (Slovenia)           | Torcrete with sand-gravel filler            | – – | 2300 |
| 4. | Loughborough University (UK)    | Cement fine-grade concrete                  | 13.0 110.0 | 2250 |
| 5. | Cy Be Construction (Netherlands) | Cement-sand concrete on mineral binder      | 6.0 45.0 | 2250 |
| 6. | Batiprint 3D (France)           | Urethane-foam casing filled with cement concrete | – 0.16 | 30 |
| 7. | MIT Media Lab (USA)             | Urethane-foam casing filled with cement concrete | – – | – |
| 8. | DUS Architects (Netherlands)    | Recycled plastic as a casing filled with light concrete mixture | – – | – |

**Table 2.** Advantages and disadvantages of technological solutions to make buildings on new generation 3D Printers

| No | A 3D printer developing company | Pros for the method of 3D print of buildings | Cons for the method of 3D print of buildings |
|----|---------------------------------|--------------------------------------------|--------------------------------------------|
| 1. | WinSun (China)                  | Based on the construction waste and disperse reinforcement with fiber | Requires large production areas and numerous staff to administer the process |
| 2. | Contour Crafting Corporation (USA) | High variability in the choice of reinforcement materials | Surface roughness, non-functional casing left behind |
| 3. | Bet Abram (Slovenia)           | The concrete contains special shrink-resistant chemical additives | Roughness of the casing used |
| 4. | Loughborough University (UK)    | High strength of structural elements, structural reinforcement | Roughness of vertical wall surfaces |
| 5. | Cy Be Construction (Netherlands) | High strength and structural Reinforcement of a building | Rough areas on the vertical wall surfaces |
| 6. | Batiprint 3D (France)           | Fast hardening process, ensuring smooth vertical surfaces | Rather low strength characteristics, requires protection from external impact factors |
| 7. | MIT Media Lab (USA)             | Mobile extruder; casing that also functions as external structural reinforcement | Uncontrollable geometrical dimensions; surface requires protection from atmospheric external impact |
| 8. | DUS Architects (Netherlands)    | Recycled materials can be used | Lengthy process for producing external and internal casings |
In this building, the architect managed to implement two parallel surfaces of the structure that folded into the infinite Moebius strips where each resulting surface acted as a ceiling or as a floor. Moreover, the structure’s external sides are flowing either outside or inside. Another peculiarity of a structure printed on an industrial 3D printer “D-Shape” authored by Enrico Dini (Italy) and made of sand mixed with a special binder is that the architectural object turned out to be one such largest building in the world made with the help of 3D print technology.

In addition to the technological methods of a 3D print described above that oriented at the making of buildings on the construction site, there is a worth-while experience of a Chinese company Zhuo Da. It took them 3 hours to build a two-story building with the module-based upsizing assemblage method. Thereat, the pre-fabricated finished modules have been decorated on the interior with decorative textures imitating marble, granite, or wood. They are equipped with engineering networks, bathroom accessories and built-in furniture. The delivered modules fully finished at a factory are assembled on the construction ground, whereupon the building is 90% ready. It only requires attendance and finish on the sections where the delivered modular elements are attached. The peculiarity of the built object made with the help of 3D printing technology on the Zhuo Da production facilities is the fact that the building can withstand the 9-score earthquake and has an increased fire-resistance with improved heat conductivity [7].

As of present, the construction time for architectural objects made with the help of 3D printers all over the world is only challenged by the lack of any coordinated policies and certain regulations or adequate construction rules and standards to systematize the conditions for the functioning of the available 3D printing machinery. They need to set the necessary terms and conditions regulating all the known technological methods and techniques to make buildings and structures meet the demand of modern architectural practices. Table 3 lists the most famous architectural objects in the world made with the help of 3D print and using the industrial 3D printers and the above-described methods for construction and application of various construction materials. The list of the 12 well-known architectural objects includes buildings and structures made with the help of 3D printing, on all continents in the world, in the period from 2003 to 2019 [8].

Table 3. Architectural objects implemented globally in 2003 – 2019 with the 3D print methods.

| No | Name, country, and a firm constructing the architectural object | Brief description of the architectural object |
|----|---------------------------------------------------------------|------------------------------------------------|
| (a) | (b) | (c) |
| 1. | Pod Skyscraper (residential building), Tokyo (Japan), Designer architect Haseef Rafiei | Multistoried residential facility with a 3D printer located on a skyscraper’s top floor |
| 2. | A complex of mass housing cottages, in cities in Latin America (Brazil, Columbia, Bolivia), Fuseproject Design Studio, Architect Yves Béhar | One-floor single-family houses for low-cost residence |
| 3. | Gaia (a building made of eco-friendly materials), Massa Lombarda (Italy), 3D printer Crane Wasp, authors: WASP architectural bureau | Architectural object made of rice residuals (straw, plant peeling waste) |
| 4. | Milestone (housing for rental), Eindhoven (Netherlands), Eindhoven University of Technology, architectural bureau: Houben & Van Mierlo Architecten | “Free form and texture” houses for rent in one-floor housing |
| No. | Project Description | Details |
|-----|---------------------|---------|
| 5.  | Skidmore (exhibition pavilion within a landscape), Skidmore (USA) Oak Ridge Laboratory, architectural firm Owings & Merrill (SOM) | Exhibition pavilion made of polymer materials. The building operates under the passive house principle |
| 6.  | Curve Appeal (resident house of complex configuration), Chicago (USA), Designer: WATG’S Urban Architecture Studio | Arch-like structure of the building contour made of carbon fiber and glass window panels |
| 7.  | Mobile Europe (resident house with a functional façade), Amsterdam (Netherlands), Architectural bureau DUS Architects | A house for living, with a facade made of special plastic produced on a bio-basis (vegetable and linseed oil) |
| 8.  | Dubai Future Foundation (office building), Dubai (UAE), Authors: Gensler, Thornton Tomasetti, Syska Hennessy (WinSun company, China) | Office building with a white façade, of futuristic shape, made with a multilayered extrusion method of concrete fine-grade mixture |
| 9.  | A residential one-floor house, Stupino (Russia), Apis Cor Company (USA), Design and engineering: Chen Jung Tai N.D. | The first building in Russia ever made with 3D print of a multilayered extruded concrete. Floor area - 38 sq.m, the construction took 24 hours, at sub-zero temperatures -20°C |
| 10. | Office building, Dubai (UAE), Apis Cor Company (USA) | The largest building in the world made with 3D print and printed directly on a construction site |
| 11. | A residential house with a frame and the interior printed on a 3D Printer, Suzhou (China), (WinSun company, China) | A mansion printed with the building’s support frame, interior partitions and the installed engineering networks |
| 12. | The sculpture restored during the restoration works, Paris (France), Архитектурно-реставраційне бюро Conc3De, architects: Eric Geboers, Matteo Baldassari | During the restoration of the Notre Dame de Paris cathedral. For a Strix gargoyles figure destroyed in the fire, they used a mixture of the building materials collected and saved on the site |

The analysis of data provided in Table 3 offers the grounds to claim that the three-dimensional print technologies are used in the world architectural practices for various functions of buildings, from public housing, to the restoration works, for present-day and future architectural needs.

3. Results and discussions
The analysis of international practices in making architectural objects engaging 3D printers leads to the following findings: the building and structures making technology has critical advantages, but also certain shortcomings.

The challenges in the process of applying 3D print in building modern architectural objects may be described as follows: 1) no coordinated position in the legal framework of all countries all over the world that are using the 3D printing technologies; 2) high cost of the 3D print machinery for architectural objects; 3) certain restrictions for the dimensions of buildings and structures preconditioned by the respective size of industrial 3D printers; 4) special conditions for the organization and size limitations for construction sites that depend on the special auxiliary machinery used; 5) lack of universal recipes for construction mixtures (concrete, polymer) recommended for the 3D print in low-cost architectural objects.
4. Conclusions
Despite the above-mentioned negative aspects of implementing 3D printers when creating architectural facilities, we need to state that the three-dimensional print in the architectural world practices contains a series of substantial advantages. They are as follows: 1) high speed and accuracy in the process of building the structures; 2) the built architectural facilities are simple in use; 3) a relatively low construction cost of buildings and structures; 4) minimized use of manual labor during construction; 5) ensuring comfortable and non-traumatic labor conditions; 6) the recyclability of construction waste when building architectural objects; 7) environmental friendliness of the constructed architectural objects due to the use of safe and natural construction materials in 3D print.

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