Using of additive manufacturing (AM) in construction economics – shortcomings, advantages, prospects

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Abstract. The article considers the topic which is currently relevant for the construction industry – competitiveness growth of construction companies in the market by application of additive technologies. 3D technologies open up new ground for the construction industry as their application allows them to construct buildings of almost any shape, therefore, designers and architects will get more freedom to implement their creative plans and ideas. Upgrading of construction technologies will reduce quantity of waste and provide higher safety level on construction sites. Innovativeness of Additive Manufacturing (additive technologies) is based on application of special equipment - a 3D printer. Intensive development of Additive Manufacturing significantly changes ratio of economic factors in construction. The author believes that profitability of companies in a new competitive context will depend not on scale of production but on quality and originality of ideas. Philosophy of the economy after the third industrial revolution will base on development of original projects and not on products manufacturing.

1. Introduction

One of the main factors for competitiveness growth of companies in the construction market is application of technological innovations. Currently, additive manufacturing or 3D printing is one of such innovations. The term brings together a whole group of technologies that use 3D printing for construction of buildings and production of building components. Essence of the technology lies in the fact that production of objects is carried out sequentially, layer by layer, in accordance with a digital (or computer, CAD) 3D model. When using 3D technologies, various materials can be used, including concrete. But, as a rule, a special mix is used for additive manufacturing in construction. Due to special additives the mix has higher density as compared with ordinary concrete that allows it to be self-supporting during its installation. Physical characteristics of the mix used for additive construction open up broad prospects for changing ordinary architecture and geometric shapes [1]. Manufacturers in various fields of economic activity are showing heightened interest in 3D printing. Over the short period of time passed since 3D printers were developed, manufacturers have learned how to use them to produce, including: interior items and furniture, small architectural forms, tableware, clothes, toys, cars, and even human organs and tissues. A construction site is a high-risk area. According to a representative of the trade Union of construction workers and the construction materials industry Boris Soshenko, on average, every year 5 workers per 100,000 perish on construction sites in Russia [2]. Whereas in
buildings construction by means of 3D technologies application of manual labor is minimized. The very idea that human participation in construction can practically be reduced to zero opens up new perspectives for society in the area. As already mentioned, application of 3D technologies allows you to construct buildings of almost any shape. Firstly, it gives designers and architects freedom to create without restrictions specified by standards. Secondly, periods of construction become shorter. By applying computer simulation to design buildings workers are able to pre-lay connectors for insulation, pipings, electrical wiring and window blocks. All these elements are installed after a 3D printing is completed. [3,4].

One can produce the following units using 3D printing in construction:
1. building structural elements (printing and laying of bricks, printing of blocks, glass, composites, beams, scaffolding, frames);
2. floors (topological optimization and printing);
3. complicated facades, frames for external structures including repair and restoration work;
4. load-bearing and curtain walls as well as linear objects (gutters, parapets, roadways including their repair);
5. small buildings, relatively uncomplicated structures (military barracks, booths, toilets, bus stops);
6. bridges, pipes for laying tunnels underground, etc.

According to data by leading international sectorial analytical company SmarTech Publishing, potential of 3D printing in construction may be comparable in scale to total volume of additive manufacturing in production and medicine [5]. Despite a fact that today the technologies are at the stage of experimentation and R&D, the market will double in the next three years and grow from $70 million to $40 billion between 2017 and 2027 respectively. At the same time, sales of materials will amount to $150 million, equipment supplies - $3.5 billion, income from printing service and its application in various fields including revenues from specialized 3D printing centers -$36 billion.

There are several additive technologies currently on the market:
1. Extrusion Based Technologies - concrete/cement, wax, foam, polymers.
2. Inkjet printing (inkjet application of a binder in a powder layer- Binder Jetting) - polymer compound, chemical compound, sintering.
3. Wire arc additive manufacturing (WAAM).

Other technologies including meshy frame forming, vertical construction forming by sliding, partial concreting of metal mesh, etc. 3D printing market of modules and bricks is also developing (modularity and bricks).

Extrusion printing of buildings and infrastructure elements took the largest share in the market (in terms of cost and volume) in 2019 due to the fact that it allows builders to produce large-scale construction components with complicated geometric structure combined with application of traditional building materials. Basically, the technology uses the following materials: concrete, metal, plastic, ceramics [6].

Ordinary cement is not suitable for production of such products, since concrete with improved quality characteristics is required. At the moment a material whose quality can meet all requirements has not been developed yet. The materials applied for construction by means of 3D technologies have a number of disadvantages. Today, these include: firstly, impossibility of concrete transmission to a higher altitude since the material begins to harden even in a pipeline, and, secondly, a fact that concrete has poor insulating characteristics so walls made of such material will transmit coldness to a residential premise. It is planned to use as a printing material sand concrete or powder concrete modified with additives of class B60 and above. Today, a group of scientists led by Professor V. I. Kalashnikov is working on such concretes at the Penza state University of architecture and construction. Composition of concrete under development surpasses existing concrete in terms of physical characteristics. Results of the tests performed showed that samples of sand concrete have high value of toughness index (over 100 MPa in compression) [7,8].

As a rule, the most common material in construction is concrete. There are the following types of concrete:
1. ready-made concrete mix;
2. prefabricated reinforced concrete;
3. shotcrete (applying a layer of concrete to concrete and reinforced concrete surfaces);
4. high-density concrete.

Most likely, housing construction will become the fastest growing segment especially in the field of low-rise construction. Demand for affordable low-rise residential buildings and ability to create complicated but inexpensive architectural constructions may be considered as key drivers for market growth. According to a final product the market also can be divided into several specialized areas producing walls, roofs, floors, stairs, etc. 3D-printed concrete walls are one of the most important construction produced in advance at a construction site or at a factory. In 2019 Europe dominated the 3D printing concrete market in value terms (including the Russian market). The Middle East is expected to become the fastest growing market of 3D printing specializing in concrete between 2018 and 2023, as dissemination of additive manufacturing in the region is stimulated by high labor costs, demand for affordable homes among middle-and low-income population, and its support by region's governments [9].

2. Research

Currently, the innovative technology named Contour Crafting is being intensively developed. Its author is Behrokh Khoshnevis from University of Southern California, the USA. In 2017 Behrokh Khoshnevis claimed that his system could build a full fledged house in one day, and construction process would generate minimum of construction waste. It was estimated in 2012 that construction generated 3-7 tons of construction debris and significant amount of exhaust gases produced by vehicles. When applying the "Contour Crafting" technology, a level of harmful impact on the environment becomes minimal. The author of the technology said that in 2017 NASA assessed prospects of applying his technology for bases construction on Mars and the Moon. The technology can be used to build lunar infrastructure, at that 90% of all necessary materials are supposed to mine on the Moon, and only 10% to brought from the Earth [10].

Additive technologies are being actively developed in China. A complex of ten 3D-printed houses with an area of 200 square meters each was built in Shanghai. WinSun, a company specializing in 3D printing using cement, builds homes that cost just $ 4,800. During its time on the market, the company has registered 77 national patents. Its huge 3D printer - 150 meters long, 10 meters wide and 6.6 meters high, builds homes in just a few hours using cement and fiberglass. Like conventional 3D printers, it "prints" buildings layer by layer, in a bottom-up direction. Remarkably, the company uses construction and industrial wastes and dumps instead of new construction materials. In the future WinSun plans to set up 100 recycling plants across the country to collect waste and turn it into building materials. Combination of 3D homes printing and application of recycled industrial materials will cut construction costs in half, the company estimates. And construction of houses using the technology will provide low-income chinese families with affordable and high-quality living area [11].

What changes can development and spread of additive technologies bring to the production sector in particular and to the world economy in general in the nearest future? The world scientific community and the media have been actively discussing the issue since the end of last year. The British weekly "The Economist" has published a number of articles about coming the Third industrial revolution, which will occur in the near future as a result of additive technologies development [12]. Making the forecast regarding the future of construction economics awaiting human community in a few decades the authors of the weekly came to the conclusion that one of the most likely changes in its economy will be disappearance of mass production as such. Grounds for such predictions are fairly simple and clear. From the point of view of economic theory, when using additive technologies, a manufacturer no longer needs to produce thousands of identical products in order to recoup his own costs. Contrary, 3D printing allows builders now to manufacture products that were previously considered too complicated to be economically effective. At its core, a 3D printing technology ideally suits for small batch production and individualization (customization) of mass production. Experts believe that spread of 3D printing in
the global construction industry will help the trends to take root, and as prices for industrial 3D printers decrease, cost of entering the market will also fall down making the area more accessible for small and medium-sized enterprises. New factors will influence on profitability of enterprises which in the future competitive environment will be determined not by the scale of production but by quality and originality of ideas. In other words, development of concepts not products manufacturing will become a backbone of the world economy after the Third industrial revolution. According to the authors and the experts of The Economist, a new industry in such situation instead of millions of cheap workers will need several hundred highly qualified 3D developers and designers [13]. According to the experts, returning of majority of industries from developing countries back to developed countries may become a logical stage in development of the Third industrial revolution. But it should be noted that such processes will only complicate a current situation on local labor markets. "3D printing will give new opportunities to local industries, but not the same as before. Previously lost jobs will not reappear, as production will need more skilled professionals, and artisans of the future must have definitely digital skills, said Carl Bass, former CEO of Autodesk, the company specializing in development of software solutions for 3D design. [14].

Application of additive technologies in construction provides significant benefits to project participants, its economy and construction ecosystem as a whole, since the following happens:

1. reduction of work time on the construction site;
2. improving quality and accuracy of construction processes;
3. reducing a number of employed workers and, consequently, saving on wages;
4. reduction of construction period/costs for manufacturing and installation of formwork /tooling or complete exclusion of tooling from construction process;
5. improving working conditions and safety;
6. reducing amount of construction waste and environmental burden on nature (construction industry is leader in terms of waste in the world).

But there are also a number of disadvantages:

1. Building's appearance. Condition of constructed surfaces may not meet all requirements, and therefore it will be necessary to carry out additional finishing works involving manual labor – plastering and facing work;
2. Restrictions in creation of long-sized construction;
3. Resistance to innovation which can delay spread of 3D printing in construction. Any new technology leading to jobs automation in an industry especially in poor regions or cities with high unemployment rates almost always has to overcome skepticism and resistance. Because construction printers significantly reduce a need for manual labor, they create less jobs for local workers. According to Phillips and James Construction Consulting, it can take up to 63 workers to build a typical home over a 4-month period. 3D printing methods significantly reduce these indicators. Reduction of construction schedule and labor costs as well as presence of human resource with necessary skills for applying the technology, can be achieved through retraining of personnel.
4. A construction technology using a 3D printer has special requirements for a construction site, in particular, a flat surface is required for laying guide rails, and continuous monitoring is required for ensuring parallelism of the rails, thus provides high accuracy of the work performed.
5. A qualified operator is required to operate a 3D printer, and a materials scientist is required to properly prepare and mix materials.
6. 3D printers are bulky construction and, therefore, they are not inexpensive to transport, place and install on a construction site. Accordingly, development of additive technologies requires substantial start-up investments - up to several million dollars in addition to ongoing maintenance costs, although industrial competition is rapidly driving down prices.
7. Today 3D printers are mainly used for low-rise and small-sized individual construction, as well as for manufacture of small architectural forms.

Despite numerous statements of construction companies appearing in the media, that "a house was printed in 24 hours", today such estimates are strongly exaggerated. Nowadays typical construction
printers using the mastered 3D printing processes are able to produce only some separate structures or their elements during this period of time [15].

What can one produce today using additive technologies?

1. 3D printing of building materials and structures, parts and components: one can print with concrete or composite materials bricks, panels, blocks, building and connecting components or unusual facade decorations included in a project;

2. 3D printing of molds and formwork, which can be used for traditional materials casting to manufacture building structures and elements, as well as all sorts of parts and components with unusual or complex designs;

3. A 3D printing of foundations and walls mainly using large-scale concrete extrusion is much cheaper and faster than manufacturing through traditional method (sometimes in 24 hours or less).

After that, one should carry out a number of works to complete construction of a house including installation of engineer communication (electricity, water supply, sewerage, gas pipeline, etc.), heating, ventilation, air conditioning, windows, doors, smart communication, flooring and roofing, surface finishing, locks inserting, etc. These works carried out by traditional methods through manual labor usually take a period of time from one week to several months [16,17].

If one evaluates available achievements of additive technologies, it will become clearly that, in general, construction printers only can automate a process of concrete extrusion. As for total cost of residential building construction, a contribution of 3D printers to the entire industry is still quite small. For example, the data on average cost of building houses in the United States as of 2017 show that fabricating cost of walls, frames/formwork, roofs is about 15%, and fabricating cost of foundations, retaining walls combined with earthworks is no more than 11% of total building value [18,19].

3. Conclusion

The era of mass construction through additive technologies has not begun yet. There are no ready-made technical solutions yet. Total average statistics are not yet formed, because every printed building is unique. Therefore, construction economics cannot be thoroughly calculated yet. There are saving and costly factors in additive production. It should be noted that there are a lot of costly factors. Therefore, today each construction site applying 3D printers is a pilot and experimental site, where they accumulate whole variety of knowledge and practical skills for additive technologies in construction. According to J'son & Partners Consulting awareness of results and advantages of 3D printing occurs at post-printer attestation, certification, standardization based on results of all required types of tests.

Such state of information-technological vacuum will accompany additive manufacturing in construction for at least another 12-15 years. But philosophy of J'son & Partners Consulting must be taken into account in terms of making decisions. Its essence is that application of additive technologies at an initial stage is expected to lead to higher costs compared to traditional construction. But one should not refuse to take the first step in that, since optimization and cost reduction of additive technologies in production will inevitably occur and a number of other advantages will also appear. That is why one must not only be within the process, but also must lead it [20].

Thus, if you consider economy of the industry in general, you may conclude that a 3D printing in construction in its current status quo is unlikely able to impact significantly on cost of housing, when the vast majority of a project is carried out by traditional ways. Construction companies have simply implemented a couple of newly developed construction systems which allowed them to make construction in whole a little bit more effective. However, the higher labor cost and an automation level of all additive construction processes are, the greater economic effect will be. Experts believe that in the future application of additive technologies will help to reduce labor costs by 80%.

Theoretically, in order for a 3D printing to master turn-key construction, one should make significant technological improvements in additive construction concept, which with varying degrees are already being prepared and tested:

1. Simultaneous application of various building materials by a printer Almost every 3D printer used today works only with a single material (usually concrete or similar material). But building construction
requires at least application of several types of materials. Technologies should in the future endow building printers with an ability to erect structures using several different materials at the same time, for example, concrete, plastic, iron, etc., which are most often used for construction.

2. Installation of specialized elements and structures. While most of building is constructed from widely used, interchangeable materials - commodity, there are many specialized elements and structures that are unlikely to be produced using additive technologies in the foreseeable future. For example, triple-glazed windows filled with nitrogen, electronic door locks, adjustable LED lighting systems and so on, since their manufacturing requires high-tech equipment. To fully automate building construction with such types of components, one should organize a workflow and automation envisaging these pre-made components in a building design, as well as their delivery to a site, installation, and configuration to a working state.

3. Specialized robots. Experts doubt that it is possible to create an universal system that can successfully produce directly on a construction site and install customized building components. Instead, it is more likely that they will eventually develop robotic systems within the industry specialized to work with certain types of elements and structures. For example, a window fitting robot that could efficiently serve several typical styles of window designs. Such approach seems to be productive for working with other building components.

4. Procedure of work with expendable materials on a construction site. A construction site of the future equipped at a basic level with a concrete 3D printers system, will look like probably a busy place imbued with a lot of different robotic systems moving continuously around a construction site to install various components. The best way to place the components would be creation of "transport container system" in which all necessary would be loaded like in an organizer, that would allow specialized robots to take components from the container as required.

5. Software development. To implement all of the above, one should develop complicated software to coordinate all processes and monitor all activities on a construction site. Currently, a general contractor executes these function within a typical construction site organizing subcontractor’s activities in order to implement a project phase by phase.

6. Software development for design. By analogy, design software should meet the similar requirements and be suitable for different construction methods and facilitate creation of unique structures with specified characteristics. Using a 3D printing you can get not merely such an advantage as reduction of construction schedule but also implementation of architectural projects which can be occurred only in that manner. For example, erection of structure with an internal duct system which can automatically turn on ventilation in presence of sunlight.

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