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Efficiency of 3D printers in Civil Engineering

A.M. Shatornaya [1]*, M.M. Chislova [2], M.A. Drozdetskaya [3], I.S. Ptuhina [4]

[1-4]*Peter the Great St. Petersburg Polytechnic University,29 Politechnicheskaya St., St. Petersburg, 195251, Russia*

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ABSTRACT

This article studies the efficiency of new technology – concrete 3D printer. The creators of this equipment argue that it can save significant amount of funds, when used for building construction. This research looks into how 3D printer can save time needed for building frame construction and how it may affect the total construction cost. In this article you can see the results of calculation of labor and material costs for two types of houses: printed with a 3D printer and made of aircrete blocks. Moreover, the percentage of profit, based on potential time saved and the total cost of a single-story building were calculated. As a result of the research, it was concluded that 3D printers will be beneficial for construction companies engaged in large-scale low-rise construction.

Content

Contact information:

1 * +7(911)7066515, alexandrashatornaya@gmail.com (Alexandra Shatornaya, Student)
2 +7(911)1126561, animashki1@mail.ru (Maria Chislova, Student)
3 +7(921)5810636, drozdetskayama@yandex.ru (Marina Drozdetskaya, Student)
4 +7(921)6482720, irena_ptah@mail.ru (Irina Ptuhina,Ph.D., Ph.D., Associate Professor)

1. Introduction

Nowadays, construction is the only completely non-automated industry. Human participation is pretty high in various stages of construction process, resulting in reduced productivity, increased mistake probability, labor costs, construction project cost and risks. 3D printing is one most developing and promising technologies today, which recently started to be used for printing building structures, apartments and houses. The relevance of this study is that the use of this technology will allow high work processes optimization, reduced cost of construction and risks associated with occupational injuries.

The usage of 3D printers in construction process is relatively new, and is considered in the article written by N. S. Mustafin, E. A. Sorokina, A. V. Ivasyuta,K. U. Jumambeckov [1-4].

The main advantages are the reduced construction duration and higher levels of work optimization. On the other hand the inability to use vertical and full reinforcement bars, might be considered as a disadvantage as it leads to a reduced strength of such structures.3D printers require a special concrete mixture [6], which suitable for layer-by-layer application; Development of normative documentation and solutions of problems with structures reinforcement [7, 8].

Russian engineer Andrei Rudenko, claims that in terms of strength and quality, printed apartments are not inferior to monolithic designs. In cold climates, hollow walls can be used as a fixed formwork for foam concrete with increased thermal insulation properties [9].

Initially, 3D printring technologies were considered suitable only for the urgent construction of a temporary dwelling [10]. Scenarios for the development of this technology were considered in detail by Sergei Zotov [11].

Figure 1. 3D printed villa by «Sanghai WinSun» company [11]

Several years ago, 3D printing began to be used by large companies such as Shanghai WinSun [12], mainly for low-rise apartment buildings. They were the first to build a 5-story residential block and country villa, using this technology (fig. 1).

According to the company's representatives, in the course of the experiment, savings achieved are about 60%of building materials and about 30% of the time, required to build a similar facility, using traditional methods. Furthermore, the composition of the construction team was reduced by five times, which means savings and a reduced risk of work-related injuries. The material used was a mixture consisting of cement, glass fibre reinforced fibreglass reinforced plastic, sand and a special hardener. The walls of such houses are almost hollow, and the strength and stability of the structure is given by the zigzag feeding of the mixture inside such walls [13].

Figure. 2. Apis-Cor 3D building printer (2016) [15]

Modern market of construction machinery and equipment has the large variety of construction printing equipment, which allows creation of low-rise buildings of various configurations [14]. In the short period of time the designs of 3D printers have evolved from large massive constructions [14], to the newest compact model that allows construction process inside the building. In2016 Russian Company Apis-Cor has presented such a printer (fig. 2). Its dimensions are 1.6 meters in diameter, 1.5 meters high, with a boom reach of 4-8.5 meters and a weight of 2.5 tons. This printer works by spinning around its axis and building structures up to 132 m2.The speed of work allows it to print a house up to 100 m2 in 24 hours. The company's developers also created their own fibre-reinforced concrete, and received the appropriate quality certificates, according to which it corresponds to the strength of ordinary concrete with the B20 mark and W6 water resistance [16]. Concrete with such technical characteristics is superior to previously used analogues with a lower strength of 1.6 MPa [5], which makes it possible to use it in construction without any reduction in quality. The use of fiber-reinforced concrete as a printer material reinforced with steel or fiberglass helps to partially solve the lack of reinforcement and protect it from moisture. There is the possibility of horizontal reinforcement - the laying of reinforcement or flat armo-frames between layers of products during printing [7]. In Russia, the development of new materials requires careful and long-term testing, which is accompanied by long processes of certification and research. This requires not only time, but also very significant funds [17]. The research in a related literature showed that 3D printing of buildings is particularly effective in low-rise buildings. In this regard, let's compare two methods of low-rise construction: a house made of aerated concrete blocks and the one, which was printed on a 3D printer. The purpose of the research is to analyse, the effectiveness of the introduction of 3D printing in construction, its impact on the cost and time of construction. To do this, there are several goals that have to be accomplished:

1) Explore possible applications in construction and learn about the necessary machines and materials
2) Study the existing analogue construction technologies and identify the most used ones.
3) Conduct a comparative analysis of the use of 3D printing and the most common construction technology using the example of a building model with the same planning solution in terms of time and cost
4) Make a conclusion on how much the introduction of 3D printing contributes to the optimization of the construction process

2. Methods and Results

The most common materials in low-rise construction are wood, brick, reinforced concrete and aerated concrete blocks. The construction duration of structures made of bricks and monolithic reinforced concrete is greater than that of logs and aerated concrete. Houses made of logs are built much faster, but at the same time are much more expensive than ones constructed of aerated concrete. Moreover, aerated concrete has good thermal insulation properties and is considered inexpensive at construction products market [18]. Walls from such masonry are built at the fastest rate and have been widely used in low-rise construction. In this regard, for comparison, we have chosen this design of the exterior walls.

During printing of 3D objects, the printer uses layer-by-layer method of structure construction. The construction works begin with the installation of a printer on the construction site, and then a special concrete mortar is prepared. It consists of cement, fiberglass or other materials, as well as a special thickener. Next, the building mixture is fed by the printer from the nozzle and the necessary construction is performed layer-by-layer. So, in the same way the whole frame of the building is gradually constructed, starting from the foundation and ending with the walls. When printing an object, part of the work cannot be performed by the printer. The whole complex or cosmetic processes such as communications laying, installation of doors and windows, roofing, external and internal finishing is carried out manually. Despite that, frame construction team could be reduced to 2-4 people [8].

In order to find out how expedient the implementation of 3D printing is, it is wise to compare the time and money spent on the construction with the most popular analogue technology for the construction of a single-storey house. To calculate the amount of work and materials, a single-storey house was chosen with dimensions following dimensions - 10mx10m and an area~100м^2 (Fig.3).

The comparison was made on structural parts: formwork, foundation, external walls, internal walls, installation of floors, ceilings and roofing.Costs for the laying of communications and engineering systems were not taken into account. It is worth noting that a 3D printer can immediately print walls with matching holes for pipes and wiring. Labor intensity and material consumption of excavation work was not taken into account, because this type of work is carried out identically.

To calculate the labor and construction time, we were guided by State elemental estimates (SEE) [19], average prices in the modern labor market and materials. A construction calculator was used to calculate the volume of materials. The foundation in both cases is tape-shaped; it is executed equally except for the formwork. In the case of the construction of a house using a traditional method of aerated concrete, when pouring the foundation, a removable timber formwork is usually used, which the builders construct within a couple of days.3D printer makes it possible to create a permanent formwork with already laid reinforcement grids in just 1 hour. The amount of concrete poured into the formwork is the same in both cases – 16, 1 m^3.

In the case of a gas-concrete house, the walls are constructed of rectangular aerated concrete blocks with the density of D600. The height of the walls is 3m.After the construction is done the enclosing walls are insulated with mineral 100 mm thick wool. Ceramic granite is used as a facing material. Blocks are connected with each other with the use of glue solution.

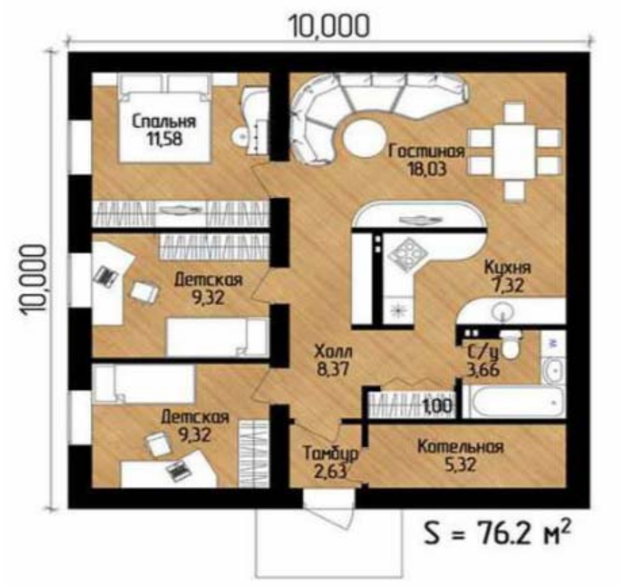

Figure. 3. House layout

The floor is wooden. The ground is levelled, the sand is compacted, then the lags are installed, which are supported by the foundation, boards are installed on top of the log. After that waterproofing and floor insulation is performed.

Attic overlap is made of glued beams 50x200mm with a pitch of 300mm; heat and sound insulation are produced. The roof is gable with a slope of 15 degrees, the roofing is metal roofing.

Now let's have a closer look at how the construction is done with the usage of 3D printer. Printing of the walls of the house is done layer by layer. Each layer is printed first along the contour, and then a zigzag lattice is printed in the cavity of the bearing walls for greater strength and stability. Through each 10-16 layers the worker puts longitudinal reinforcement. First of all, there is a printing of bearing walls, then installation of prefabricated floor slabs, and the last stage is the seals printing. To calculate the required volume of fibre-reinforced concrete, such things as the house layout, wall thickness, opening dimensions and thickness of the feed layer from the printer nozzle were taken into account. During printing, a transverse reinforcement d = 10 mm with 50 cm intervals is installed along the perimeter after every 40 cm of height.

Of the labor costs for printing walls and formwork of the foundation, only 2 specialists are required: one 3D printer driver and one assistant. The printing of bearing walls is done in one working shift. During the next shift the installation of a wooden floor (the same as in a gas-aerated analogue) is completed. For the third shift, partitions are printed and the house is finished. Based on the results of the calculation, we obtained three comparative tables for the two construction options. Tables 1 and 2 show the costs of materials. Table 3 shows the calculation of labor costs and the timing of work.

Table 1. Cost of materials with aerated concrete

Name of works		Quantity	Unit of measure	Material cost, rub		Total, RUB (USD)
				For a piece	Total	
Foun-dation	timbering 50x100x6000mm	119.0	119.00	260	30940	111419 (1950)
	concrete B20 (P3), m3:	19,9	19.90	3060	60894	
	steel framework D=14mm, m/rm	298.0	360.58	36.32	13096	
	steel framework D=6mm, m/rm	271.0	60.16	7.75	466	
	Installation EFP, m3/pac	8.6	33.22	150	4983	
	Installation stud, pcs/pac	172.0	1.00	1040	1040	
Walls	Aerated concrete: D600, 625x250x400mm, м3/ м3 in pac	68.7	69.42	4250	295035	345873 (6050)
	glue, kg/pac	2473.0	98.92	228	22554	
	steel framework, m2/pcs	322.9	129.15	219	28284	
Total cost						457292 (8000)

Table 2. Cost of materials with 3D printed walls.

Name of works		Quantity	Unit of measure	Material cost, rub		Total, RUB (USD)
				For a piece	Total	
Foun-dation	permanent formwork, fibre concrete B20 W6 P1	0.93	1.00	4000	4000	76965 (1350)
	concrete B20 (П3), м3:	19,9	19.90	3060	60894	
	bar mat D=5mm, m2/pcs	90.0	36.00	168	6048	
	Installation EFP, m3/pac	8.6	33.22	150	4983	
	Installation stud, pcs/pac	172.0	1.00	1040	1040	
Walls	steel fiber concrete, B20 W6 P1	14.75	15.00	4000	60000	67877 (1190)
	steel framework, D=14mm, m/rm	155.0	187.55	42	7877	
Total cost						144842 (2540)

Table 3. Calculations of work time on walls and basement [18].

Name of works		Unit of measure	V	Workers per shift	Number of shifts	Duration, work days per 8 hours
Walls	Aerated concrete	for 1 m	72.2	2	1	10.48
	3D printing	for 1 m3	14.75	3	1	2.15
Formwork	installation	for 1 m2	71.4	2	1	2.80
	3D printing	10m/min	2620	1	1	0.52
Installation fittings	full frame	for 1 frame	424	3	2	3.20
	reinforcing mesh	pieces	36	1	1	0.50
Concrete placement		for 1 m3	19.9	2	1	0.40
formwork	removal	for 1 m2	71.4	2	1	0.67

The final results of the analysis are given in Table 4. The table separately presents materials and labor. Also a comparative analysis of the duration of the work, including similar work, was carried out. Based on the obtained data, the percentage of benefit is shown when using 3D printing technology house construction in a current situation.

Furthermore, the duration of the work is also added 7 days for a set of half strength concrete foundation. When using a 3D printer, reinforcement in the foundation process is easier as it is possible to put a longitudinal: reinforcing mesh, without tying them. This allows you to reduce the time to install complete frames and the corresponding labor costs. In the case of the construction of a house in the usual way, it is allowed to use a fixed formwork of the basement. As for this house, it will cost at least 27 thousand rubles. However, when it comes to constructing the whole cottage community, it is more profitable to purchase one demountable formwork, which can be reused on other typical objects.

Table 4. Comparative analyse.

Construction phase	Cost, rub				Construction period, days	
	Of materials		Of works			
	Aerated concrete:	3D printer	Aerated concrete:	3D printer	Aerated concrete:	3D printer
Formwork	30 940	4 000	9 896	2 445	2.8	0.5
Walls	345 873	6 877	31 462	10 038	10.5	3.0
Foundation	111 419	76 965	44 184	4 202	14.07	8.42
Insulation	200 191		120 000		10	
Paul	185 742		50 800		10	
Overlap	121 304		21 600		7	
Roof	180 645		204 880		22	
Subtotal:	1145174	832724	472925	411520	53.2	40.1
Total cost RUB (USD)	Aerated concrete:	1 618 099 (28 325 $)		Total duration		
	3D printer	1 244 244 (21 780 $)				
Saving of cost%:	23.1			Saving of time, %:	24.6	

3. Discussion

The benefit of time and cost, without taking into account the cost or rental of equipment for construction is no more than 25%. If the same frames are made for the foundation, then it will be about 20%.Printer manufactures declare about saving of the general cost price to 15% due to foundation works. According to calculations, the savings from this type of work amounted to 5%. The greatest savings are achieved with wall construction - 18% of the total house cost, while the producers of the innovative printer Apis-Cor claim that it is possible to save up to 25% on the frame construction [16].

If we consider separately the savings for specific stages of construction, then on the foundation works, savings are up to 50% at a cost and up to 40% in terms of time. Printing walls on a 3D printer saves up to 80% of the cost of this type of work, while performing them three times as fast. At the same time, the creators of 3D printers develop their technology and building structures as close as possible to the existing standards for reinforced concrete products in terms of strength, stability and quality.

Based on the proposed prices in the construction equipment market, the average cost of a 3D printer can be 2 million rubles. If it is acquired by a construction company for the construction of a cottage community or a private low-rise building, taking into account the savings on each house of 370 thousand rubles, the printer will pay for itself at the sixth house.

4. Conclusion

1) As research has shown, the introduction of a 3D printer can be very beneficial for construction companies. In the best way, at this point in time, the printer shows itself in low-rise construction. It can also be effective in cases of the need for urgent construction of temporary housing after natural disasters.

2) Among existing analogues of houses in low-rise construction, aerated concrete is closest to the price and time characteristics of a 3D printer, which is optimal for comparative analysis.

3) A comparative analysis showed that for private construction, the use of this technology, taking into account leases, can be beneficial only in terms of construction time, the costs will remain approximately the same. In the perspective of construction companies this technology can prove to be effective as it will allow to optimize the technology of production.

4) 3D printing technology will allow the construction of buildings faster and save up to 23% of the cost of construction and up to 25% of the construction time when accounting for the construction of a single-storey cottage without interior finishing and the installation of utility networks.

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Эффективность 3D принтеров в строительстве

А.М. Шаторная [1], М.М. Числова [2], М.А. Дроздецкая [3] И.С. Птухин [4]

[1-4]Санкт-Петербургский политехнический университет Петра Великого, 195251, Россия, г. Санкт-Петербург, Политехническая ул., 29.

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ИСТОРИЯ

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КЛЮЧЕВЫЕ СЛОВА

3D печать;
строительные принтеры;
оптимизация строительства;
фибробетон;

АННОТАЦИЯ

В статье изучена эффективность использования новой технологии в строительстве- бетонных 3D принтеров. Создатели данного оборудования утверждают что, с их помощью можно сэкономить значительные средства на строительстве нового здания. В этой статье рассматривается, как можно сэкономить время на возведение каркаса здания с помощью 3D-принтера и как изменится окончательная стоимость строительства. В данной статье вы можете увидеть результаты расчета затрат труда и материальных затрат для двух типов домов: напечатанный с помощью 3D принтера и выполненный из газобетонных блоков. Так же был рассчитан процент прибыли за счет экономии во времени и общая стоимость одноэтажного здания. В результате исследования сделан вывод, что 3D принтеры будут выгодны для строительных компаний, занимающихся масштабным малоэтажным строительством.

Контакты авторов:

1* +7(911)7066515, alexandrashatornaya@gmail.com (Шаторная Александра Максимовна, студент)
2 +7(911)1126561, animashki1@mail.ru (Числова Мария Михайловна, студент)
3 +7(921)5810636, drozdetskayama@yandex.ru (Дроздецкая Марина Александровна, студент)
4 +7(921)6482720, irena_ptah@mail.ru (Птухина Ирина Станиславовна, к.т.н., доцент)

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