Feasibility of construction of buildings with the 3D printing concrete from different methods perspectives focusing on economic evaluation

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Abstract:

3D printed concrete (3DPC) is one of the new and promising techniques in the movement toward the automation of construction processes. As it has been proven, the requirement of industrialization and expansion of technology is its efficiency from different perspectives. Paying attention to the economic evaluation and cost-effectiveness of that method is one of the most important points. The purpose of this study is to investigate the feasibility of building production using the 3DPC method. The evaluation factors of different landscapes including cost, time, quality, labor, safety, and environmental issues have been briefly reviewed. For economic evaluation between different construction methods, based on experimental studies, the direct costs of construction (including frame and internal and external walls) of a typical residential building were determined. The economic evaluation results show that although the cost per cubic meter of 3D printed concrete is more than 2 times the cost of normal concrete, 3D printed concrete has lower direct construction costs than other traditional construction methods so that On average, this method reduces the direct construction costs for such a building by 23%. Its main reason is to eliminate molding, optimal use of materials, and minimum waste of materials. The economic advantage of this method is improved by a significant reduction in time.

Keywords: 3D printing concrete, cost, automation, economic evaluation, evaluation factors

1. Introduction

Having a safe shelter is one of the basic human needs. Due to the increasing rate of construction around the world, the construction industry is currently facing a shortage of materials, which leads to the high cost of materials. Also, a labor shortage is another problem in this industry. An increase in the cost of materials and labor causes an increase in construction costs. Even today, in the modern age of automation in every field, the construction industry is still based on traditional construction methods. Therefore, there is an urgent demand to transform and improve the practices of this industry with various construction automation technologies [1]. 3DPC is an emerging technique for constructing buildings and infrastructures. 3DPC is one of the types of additive manufacturing (AM) that includes all modern techniques of building elements layer by layer [2-4].

Today, 3D printing is experiencing an exponential increase in terms of research and application activities and is continuously progressing [5]. The use of 3DPC technology in construction is considered a new era for the industry due to its potential in creating changes in conventional construction methods [6]. Due to its unique features, such as mold-free construction, reduced human involvement, minimal wastage of materials, higher shape complexity due to the lack of time-consuming molds, mass customization, geometric freedom and flexibility, and structural design. More efficiency, which leads to more stable structures, is considered desirable [7]. This technology completely saves formwork costs, reduces labor costs by 50-80% [8], and reduces the waste of construction materials on the site by 30-

60% [9, 10]. In addition, due to the increase in productivity at the construction site and reduction in construction time, it has the potential to further reduce construction costs [3, 11, 12].

The 3D printing construction market is expected to grow by around 250% between 2019 and 2024. The market for 3D printed structures is growing at a fast pace due to the high demand for complex structures in the building and infrastructure sectors. 3D printing is considered an important tool for the third industrial revolution [1].

The main concern of the consumer to adopt new technology is the costs imposed and issues related to the technology, if the cost associated with it is more than the traditional method, even if there are advantages over the old method. Anyone would be hesitant to adopt a relatively new method. Only a few studies have been conducted on the cost analysis of 3DPC [13]. Most of the studies have focused on comparing 3DPC with traditional concrete and less on other construction methods.

The purpose of this study is to analyze the economic impact of 3D printing technology in building construction and compare it with other traditional construction methods. The capital cost of the 3D printing system can be considered similar to the investment of primary assets in traditional construction [1]. It is very difficult to assess the costs associated with pre-construction investments. Therefore, in this research, the direct costs related to construction are considered only. All other works such as plumbing, electrical, woodwork, and finishing works are carried out among similar construction methods.

2. Evaluation factors

In general, examining a subject from different perspectives may show different results. In the discussion of evaluating the 3D printing method of buildings, this issue can be looked at from different perspectives. Overall, relatively limited studies have investigated this issue, and often the focus has been on examining the costs and time of projects in this way. In this study, in addition to examining this issue from the perspective of cost, other aspects are also briefly discussed.

2.1. Cost

Cost is one of the three main pillars of any project. In general, for a construction method to become widespread, it is necessary for its costs to be known [14, 15]. It has been widely stated in the literature that the use of 3D printing in buildings leads to a great reduction in costs due to the elimination of molding, reduction of labor, and construction time. These findings are still under debate and conflicting opinions have been reported [3, 16, 17]. There is a lot of literature on the cost analysis of metal, polymer, and ceramic-based 3D printed parts used in the construction sector. However, in this study, the focus is on the research that has been done regarding 3DPC. Table 1 summarizes the studies conducted in the economic evaluation of 3DPC structures.

Table 1. An overview of the studies in the economic evaluation of 3DPC

Study	Result	Year	Ref.
Buswell et al.	Due to the need for a skilled operator and accuracy in providing the concrete mixture in the 3DPC, the widespread use of this technology is currently considered impossible to some extent.	2018	[18]
Khoshnevis et al. & Labonnote et al.	The ability to produce complex 3D shapes is the most attractive feature of 3DPC compared to traditional processes, not cost savings.	1998 2016	[17, 19]
Schutter et al.	3DPC material costs can be lower than conventional construction costs (less material waste). Still, they may be higher than traditional costs if expensive additives such as nano clay, nano-silica, and certain chemical additives are present.	2018	[3]
Yang et al.	They stated that, unlike conventional construction, there is no general understanding, and no pricing basis for 3DPC, which may lead to a large deviation from the actual cost calculation. Therefore, the authors proposed an accurate method for calculating the cost of 3DPC structures on-site and off-site but did not show a cost-saving case study.	2018	[20]
Mechtcherine et al.	Formwork accounts for about 30% of the total cost of structural work, even for simple geometric configurations so 3DPC can provide significant cost savings.	2019	[21]
Schmitt	Formworks were found to be responsible for 28% of costs, which may be higher depending on complexity due to labor costs and the time required.	2001	[22]
Aïtcin	They investigated the cost and product comparison for additive manufacturing technology versus the traditional concreting method. The authors considered a hypothetical structure of a wall 20 m long, 0.305 m thick, and 4 m high. According to them, the cost of using this technology was about traditional construction. But due to the higher efficiency of using 3DPC technology and converting it into a cost, 3D printing technology is more affordable.	2016	[23]
Ji et al.	They printed an electricity distribution post. The authors reported a 30% reduction in execution time and a 60% saving in material waste compared to traditional construction methods. Also, a cleaner and tidier construction site was achieved by reducing dust pollution.	2019	[24]
Näther et al.	Between the 3DPC and traditional masonry structures, a total cost savings of about 25% and a four- to six-fold reduction in execution time were achieved. The main cost savings was workers' salaries, which was about 85 percent, followed by materials, which were down about 20 percent. Equipment costs, which were about 5% of the total cost, increased by 265% with 3DPC.	2019 2017	[21, 25]
Soto et al.	reported that the cost structure of 3DPC is significantly different compared to conventional construction.	2018	[26]
Schach et al.	According to the authors, traditional masonry structures make up 75% of the total construction in Germany, whose wall area is about 35,000,000 meters. If only 1% of walls are printed by this technology, the current result would be 350,000 meters of printed walls and a market volume of 20 million euros.	2017	[27]
Yang et al.	According to them, this technology effectively reduces energy consumption and the amount of waste. They claimed that 3DPC may reduce construction material consumption by 60 percent, construction time by 50 to 70 percent, and labor costs by 50 to 80 percent.	2018	[20]

It is generally accepted that costs are divided into two categories: direct costs, including the cost of materials, construction, labor, equipment, and indirect costs, including overhead costs, taxes, insurance, administrative costs, and profit.

In terms of construction costs, it should be noted that considering only the construction of walls and structural vertical components is done through 3D printing and other processes such as roof components, joinery, and implementation of facilities, is similar to other techniques including ordinary concrete and masonry buildings, are considered the same for the estimation of the total project costs, the cost of similar activities, in different techniques.

2.2. Time

In addition to cost, time is also a very important parameter in construction projects in such a way that it is necessary for projects to be efficient both economically and time-wise. The shorter the construction time, the faster the return on investment; As a result, the total costs of the project are reduced and the investment profit is increased [28]. This factor is especially prominent in economies with inflation. Considering that 3DPC can be used only in the frame and structure of the building, and in other parts such as carpentry and mechanical and electrical installations, the process is the same as traditional conventional techniques, only in that part it is possible to reduce Project time helped [4, 26].

Various studies [29, 30] have investigated the project time and Batikha et al. [28] based on various studies have presented the following relationship to estimate the construction time of a two-story building using the 3D printing method;

$$\text{Time (days)} = 0.074 \times (\text{total area in square meters}) + 15 \qquad \text{(Equation 1)}$$

2.3. Labor

One of the basic pillars in the construction industry projects is the labor issue. Stopping or delaying projects due to problems in this pillar is a common thing. One of the advantages that are always raised for the construction of automation is the significant reduction of labor, especially in areas that suffer from a lack of labor (even simple labor) [31]. Various studies state that construction in this way can reduce 50-80% of labor on the site [9, 32]. In addition, it is clear that, by reducing the number of people present on the site, the issues of human resource management, costs. are also largely resolved. Batikha et al. [28] showed that 3D printing reduces labor requirements by 50% compared to conventional construction methods. However, compared to the prefabricated construction method, more labor is still required.

2.4. Quality

Providing appropriate and desirable quality in projects is one of the basic challenges of the construction industry, and in other words, any industry. Achieving the right quality in a project depends on various parameters that are not included in this study. In the traditional construction method, the performance and in other words the skill of the human resources present in the project is one of the important factors in the quality of the projects. Therefore, in this regard, the issue of human resource management is always raised [33, 34]. Considering that the 3D printing process of the building leads to the reduction of labor and the maximum elimination of human intervention, and the process is based on mechanical systems, the number of errors and defects can even approach zero. The accuracy of automation processes has always led to the improvement of quality in other industries [35].

2.5. Safety

The construction industry is one of the most dangerous industries in the world [36] so about one-third of accidents and deaths occur in this industry. This phenomenon is under the influence of various factors, which include the human behavior of the workforce, overcrowding in the workshop. It can be said that when the presence of labor in the project processes is eliminated or minimized, the possibility of accidents, especially the physical injuries of the people present in the project, is reduced. The regularity of construction sites by 3DPC will also add to this reason [37, 38].

2.6. Architecture

One of the important aspects of any structure and building is its architecture. Because at first glance, this architecture is a building that attracts people. One of the limitations of using traditional construction methods is architectural limitations. It may be possible to provide a special and complex architecture in certain structures, but it will definitely increase the cost, time, and complications of the project. One of the basic advantages of 3DPC is the possibility of implementing and building structures with geometric freedom and flexibility, and in other words, it leads to more efficient structural design [7, 21, 39].

2.7. Environmentally-friendly

Considering that concrete is a widely used material in the construction industry all over the world, and because it is mainly based on cement, this material plays an essential role in the emission of greenhouse gases, especially carbon dioxide gas. Therefore, researchers are always looking for solutions to reduce or replace the consumption of cement with other materials [40-42]. Regarding the concrete used for printing structures, depending on the mixture design, considering that these mixtures contain higher amounts of cement than normal concrete, they produce more CO_2 per cubic meter of concrete, which is proven by various studies [13, 43]. But due to the hollow structure and optimal geometry of printed structures, these structures consume less concrete per square meter and studies show [28] that this construction method is compared to other methods even in metal structures. They produce less CO_2. It seems that this method can be environmentally friendly, and even by using cement substitutes in the mix design of these concretes, they can be more stable.

2.8. Weight of the structure

As it is known, the weight of metal frame structures is much smaller than concrete structures. On the other hand, it has been determined that the forces acting on the structure due to an earthquake have a direct relationship with the weight of the structure, therefore, in terms of examining the forces acting on the structure due to an earthquake, it is necessary to pay attention to this issue. Studies [28] have shown that 3DPC structures have more weight per unit area than conventional reinforced concrete and steel structures and less weight than prefabricated structures.

3. Research method

As it is known, one of the challenges of using 3DPC is economic issues and cost evaluation. Most of the studies conducted in this regard have compared the construction cost of this method with ordinary concrete, but in a closer examination, it seems that only the evaluation of the cost with the ordinary concrete construction method is not enough, and other methods should also be considered. Because the ultimate goal is the construction of the desired structure, not the method of its construction. In this research, only the direct costs related to construction are considered. All similar processes and works among different methods, such as roof implementation, carpentry, installations, are assumed to be similar and are not directly included in the calculations. The cost evaluation is calculated based on the price rate in Iran in 2022. It should be noted that the used mixtures design is determined based on experimental studies. Also, in estimating the costs of other construction methods, the design of the structure and the determination of the dimensions of the elements have been based on the relevant standards.

3.1. Architectural details

To evaluate the construction of 3D printing with other construction methods, a hypothetical one-story house with an area of 77 m^2 is considered (Figure 1). One of the basic differences in different construction systems is the difference in the load-bearing components of the structure and the details of the internal and external walls of the building. In the construction of a concrete frame or steel frame, reinforced concrete or steel beams and columns are implemented and these components play a load-bearing role. Regarding the walls in these methods, ordinary cement blocks with cement sand mortar have been used, and the width of the inner and outer walls is 10 and 20 cm, respectively. In the methods of 3D printing and masonry construction, because the walls are load-bearing, their width is increased so that the width of the masonry frame reaches 20 and 35 cm for internal and external walls. Of course, the printed walls are hollow sections and consist of two outer horizontal layers with a width of 4 cm and a diagonal layer that connects these layers together. Architectural details of internal and external walls of different construction methods are shown in Figures 1 and 2.

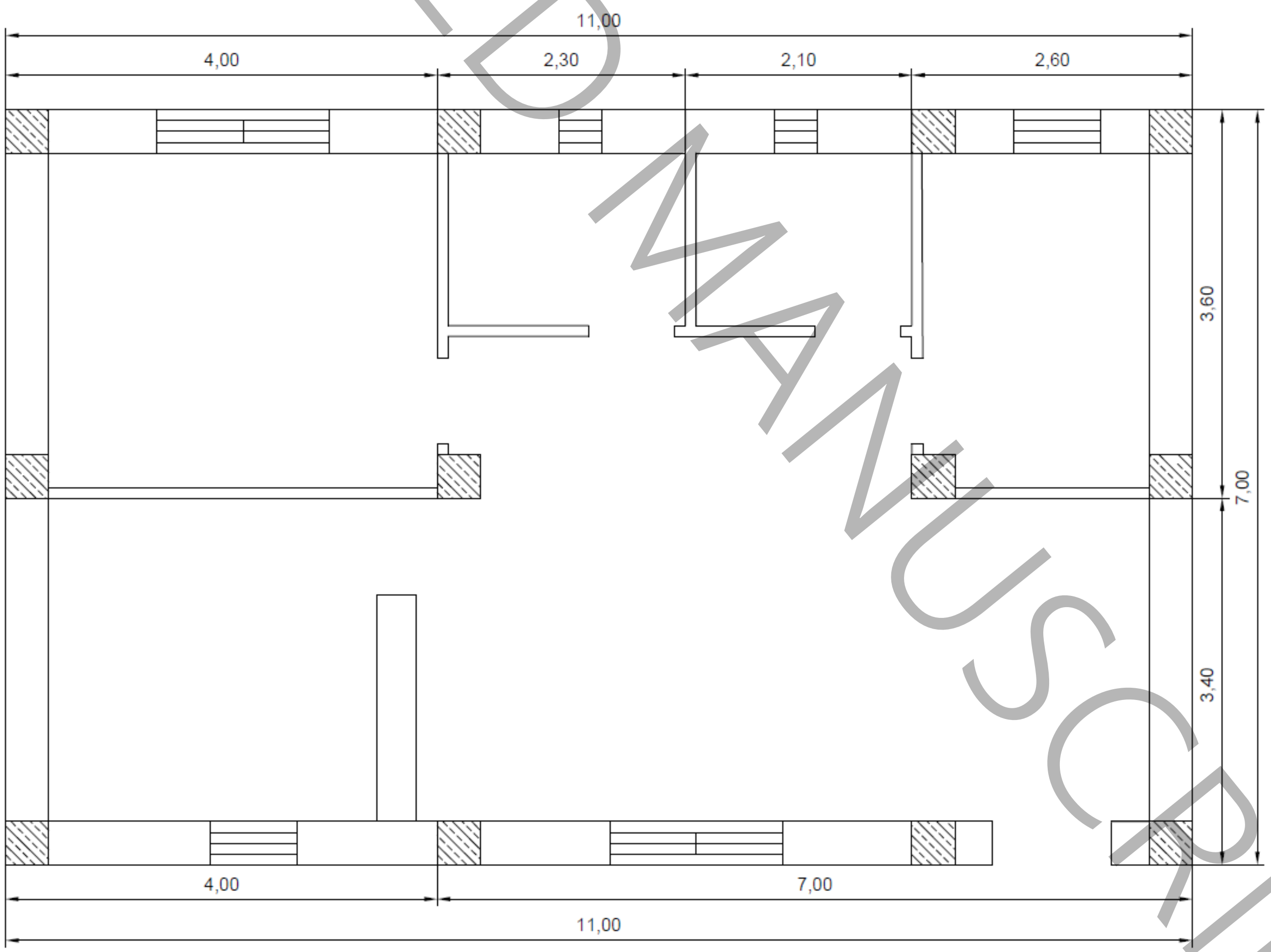

Fig. 1. Plan of the investigated building.

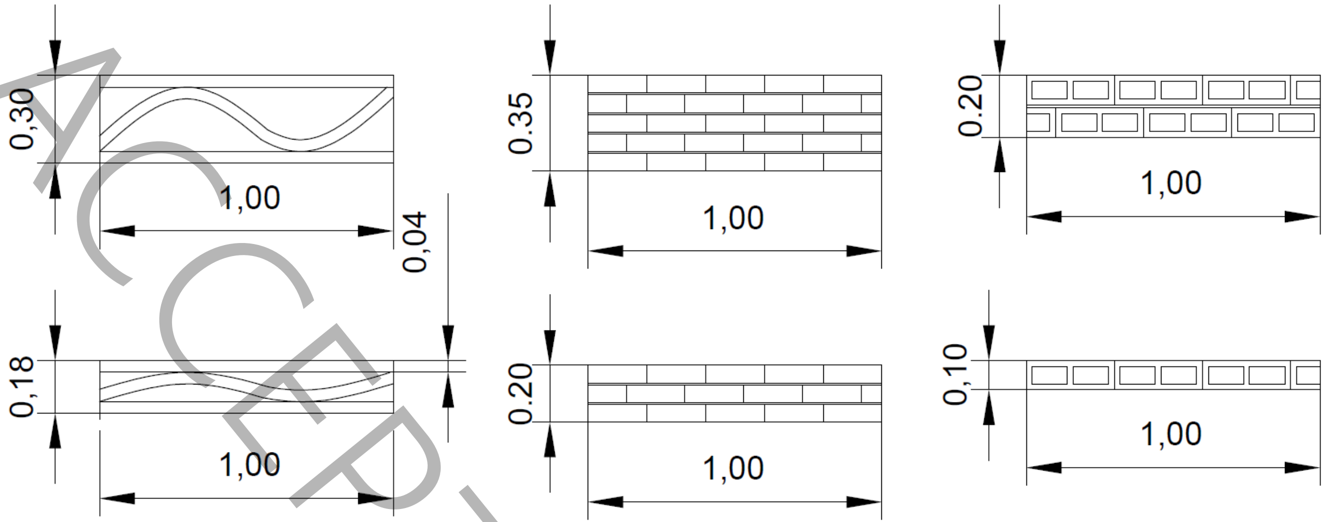

Fig. 2. Details of internal and external walls of different construction methods; a) 3DPC, b) masonry structures, c) concrete and metal structures

Local and available materials have been used in this study. The mix design used for printed concrete and normal concrete can be seen in Table 2. As can be seen from Table 2, the amount of cement used in 3DPC has doubled compared to ordinary concrete, and the ratio of water to cement has decreased significantly. Also, rolled steel sections with a yield stress of 240 MPa have been used for steel frame structures.

Table 2. Mix design used for 3DPC and conventional concrete

Materials	3DPC (Kg/m^3)	conventional concrete (Kg/m^3)
Aggregate	1350	1775
Cement	630	350
Micro silica	70	--
Water	250	175
Additives	6.3	--

4. Discussion

4.1. Cost of materials

To evaluate the construction costs between different methods, first, the cost of running a cubic meter of ordinary concrete and printed concrete and building materials was calculated (Table 3). Also, the unit length cost for the used steel beam and column sections was calculated.

Table 3. The cost of components of the mixed design used for 3DPC and conventional concrete $ (million tomans)

Materials	3DPC	conventional concrete	Masonry
Brick	--	--	13.73 (0.549)
Aggregate	6.08 (0.243)	7.99 (0.319)	1.2 (0.048)
Cement	13.86 (0.554)	7.7 (0.308)	1.15 (0.046)
Micro silica	2.8 (0.112)	--	--

Water	10.24 (0.41)	--	--
Total cost	32.98 (1.319)	15.69 (0.627)	16.08 (0.643)

According to Table 3, the cost of one cubic meter of 3DPC is more than 2 times that of ordinary concrete and building materials (110 and 105% increase, respectively). The use of more cement materials, especially micro-silica and chemical additives in 3DPC is the reason for increasing the cost compared to ordinary concrete [44-46]. For example, the cost of adding microsilica in the mix design of 3DPC is about 8.5% of the total cost. In masonry materials, although there is the cost of cement and aggregates like conventional concrete, but its amount is much less. The main cost per cubic meter of masonry materials is related to pressed bricks and the mortar used is only responsible for the connection between them. However, the cost per cubic meter of masonry materials and conventional concrete is close to each other.

Although the cost of one cubic meter of this concrete is higher, due to the hollow structure and optimal use of materials [7], the amount of concrete used in this method is lower than the conventional concreting method per unit of the wall surface. This causes the cost of 3DPC to be lower than ordinary concrete and even building materials per unit area, and its use is justified from an economic point of view. So that the amount of concrete used per surface unit in the printed structure is equal to 0.23 cubic meters. While in the concrete frame method, this amount reaches 0.28 cubic meters in one square meter of surface. The results are consistent with previous studies [13].

4.2. Direct construction costs

As stated in the previous section, in this study, only the direct costs of building the skeleton and walls (except the roof) have been calculated, taking into account materials, labor, and equipment. The costs of each construction method are shown separately in Table 4. Among the construction methods, only in the concrete frame, there is the cost of installing and applying the formwork. Also, in the masonry frame method, due to the presence of vertical ties, amounts of concrete and rebar are used, which have been considered for the cost of materials and labor and its construction.

Table 4. Separation of the costs of parts in different manufacturing methods $ (million tomans)

Construction method	3DPC	Masonry frame	Concrete frame	Steel frame
Concrete	1227 (49.08)	160.5 (6.42)	257 (10.28)	--
Rebar	--	236.75 (9.47)	688 (27.52)	--
Steel Sections	--	--	--	1403.5 (56.14)
Formatting	--	--	516.75 (20.67)	--
Chinese wall	--	1003.75 (40.15)	420 (16.8)	426.5 (17.06)
Total construction cost	1227 (49.08)	1401 (56.04)	1882 (75.28)	1830 (73.2)
Cost per unit area	15.93 (0.64)	18.19 (0.73)	24.44 (0.98)	23.77 (0.95)

Also, Figure 3 shows the cost values of each different method. Based on the results obtained from Table 4 and Figure 3, it is clear that the cost of each square meter of the structure using the 3D printing method is lower than other methods, which is consistent with the literature [13, 26, 28].The direct construction costs in the 3D printing method are 49.08 million Tomans, which is 0.64 million Tomans per surface unit, considering the area of the structure plan.

The cost of building two methods of concrete and steel frame is almost similar and is higher than other values. The results show that using the 3DPC in the construction of this building causes a 12% reduction in construction costs compared to the use of masonry materials and a 34% reduction in costs compared to concrete and steel frames. Molding has increased the costs of the concrete frame method and is significantly different from the 3D printing method [9].

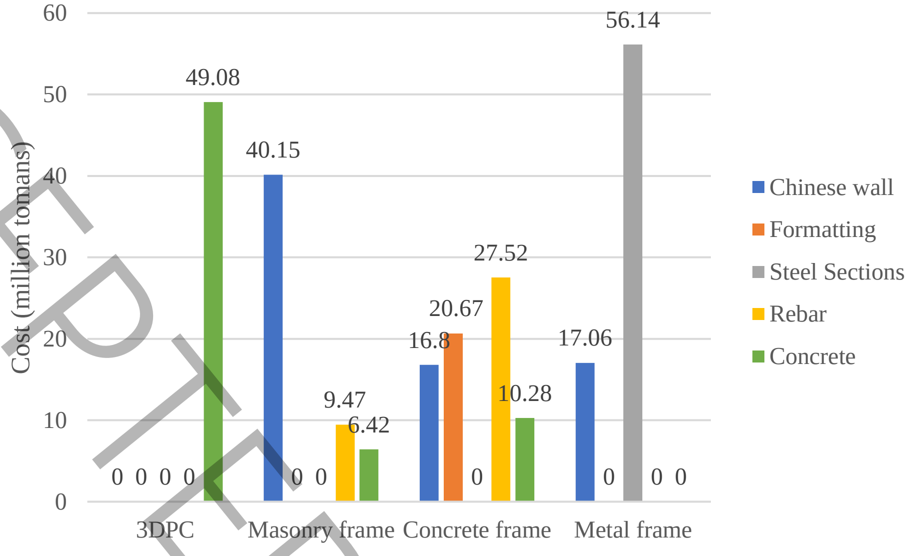

Fig. 3. The cost of different construction methods by item (million tomans)

It is clear that the final cost of the structure is obtained by adding the cost of other similar processes and activities among these methods, including the roof and the costs of carpentry and facilities, to the direct costs of construction. Therefore, by adding other costs, the total cost reduction percentage of the 3D printing method will be lower compared to other construction methods. In fact, the difference between the cost of different construction methods will be smaller [13, 28, 40].

Figure 4 also shows the percentage share of the cost of each of the frame construction components in different methods. It is clear that in 3D printing and masonry frame methods, the majority of direct construction costs are related to one process, but in the case of the other two methods, especially concrete frame, the variety of effective factors increases. Only in the construction with the concrete frame method, the cost of molding is raised, which has a share of about 27% of the direct construction costs.

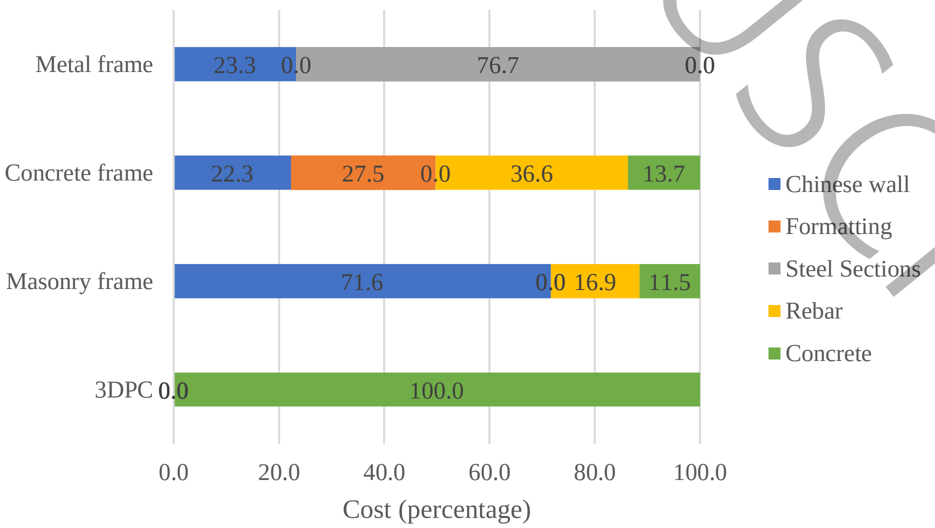

Fig 4. The cost of different manufacturing methods by item (percentage)

It should be noted that in this study, only a part of the final costs of the construction of the structure has been considered, and for a more accurate evaluation of different construction methods, different factors should be considered. The impact of more complex architecture, increase in quality, a significant reduction in time. should also be seen in the costs. Even in terms of materials that make up the major part of the costs of 3DPC, the use of cement substitutes and reducing the amount of cement used can contribute to the economic advantage of these concretes. It is also necessary to mention that this construction method is still in its early stages and more additional studies should be done, especially on its durability and performance, so that it can finally be introduced as a desirable option.

5. Conclusion

The 3DPC is one of the new construction techniques that has received great attention due to its unique features. Freedom of architecture, significant reduction of construction time, reduction of wastage of materials, and increase of quality are among these things. In the evaluation of a construction method, different architectures can be considered, and the cost is one of the most important factors in the development of a construction method. In this study, the evaluation of 3DPC method compared to the traditional construction methods is done by comparing the cost. The results show that;

• The cost of each cubic meter of concrete used in the 3D printing method is more than 2 times the cost of masonry materials and ordinary concrete. The use of high amounts of cement materials in the design of the mixture of these materials is one of the reasons.

• Even with the higher cost of materials, the 3DPC method has a greater economic advantage than other methods and reduces construction costs.

• Eliminating the cost of molding, reducing the labor force, and reducing the amount of material consumption per unit area, respectively, reduces the costs of this method by 12% and 34% compared to the masonry frame and the concrete and steel frame.

• Increasing the speed of project construction, especially in turbulent economies, will greatly help to reduce the final cost of the project.

• By using cement substitutes and new materials, the unit cost of this method can be reduced and the economic advantage of this method can be increased.

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