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Creating A 3D Printed Residential Building in Qatif

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ABSTRACT

3D printing technologies enable physical objects to be produced from digital design data, created using computer aided design software (CAD), or by digitizing the shape of existing objects using a 3D scanner. 3D printing, also known as rapid prototyping and solid freeform fabrication, is widely used by engineers and industrial designers, to make physical prototypes. In the present paper, a study is conducted on building systems and compare 3d printing and traditional house. Specific parameters are highlighted - concerning construction cost, material, time of construction, Labor cost, machine cost, sustainable aspects, and a classification method are introduced.
The objective is to explicitly characterize construction systems based on such printing processes. A cartography of the different approaches and subsequent robotic complexity is proposed. The state of the art gathered from the literature is mapped thanks to this classification. It appears that the disruption potential brought by concrete 3D printing has not been fully embraced yet. For the limited need of labor in 3D printed building which cost less than concrete conventional building. And when it comes to time, it takes less period than a regular concrete building.

1. Introduction

Three-dimensional (3D) printed building is an advanced technique of constructing an area by the computer in a geometrical shape without using tools, dies, and fixtures. The decreased costs in the manufacturing process resulted in solving the issue of formwork waste, building in limited time, and with less human intervention. However, interior designers and clients in Qatif city do not consider 3D printing in the building of their houses. On the contrary, they are still concentrating on the old traditional way of building mainly with the labor force, tools, and fixtures.

3D printing multifunctional building structures with high toughness matrix has been developed to fabricate complex 3D structures with a hierarchical nacre-inspired BM architecture. The success in eggshells is based on speed in printing [1]. The shotcrete 3D printing (SC3DP) technique was done a layer-by-layer deposition around the area. Then, laminar application with rotational movement. The variation of application is determined by the angle and the control of the layer thickness by robot speed (V). The nozzle distance (H) controls the width of the layer, and the line laser determines the in-situ measurement of the layer distance and width. It works in synchronous, cooperative, and separate ways. It contains an integrated spindle for milling and sawing, and it performs other tasks, such as picking up different tools, holding a shield or temporary formwork for slip forming, and giving temporary support. For example, in the case of notches, window cutouts, or flat angles. Another example is for holding trowels for processing surfaces such as increasing surface precision or decreasing surface roughness [2].

However, the traditional building technique is divided into four systems. The first is the foundation system which contains a grid of independent piers or poles, concrete slabs-on grade, crawl spaces enclosed, basements wholly below grade and foundation utilize a combination of bearing walls, columns, and piers. The second is the floor system which contains concrete beams, concrete slabs, prestressed concrete, and concrete formwork and shoring. The third is a wall system that includes concrete columns, concrete walls, concrete formwork, and concrete surfacing. Lastly, the roof system includes roof slopes, reinforced concrete roof slabs, and precast concretes [3].

The 3D printed house components include 1) the printers: which are created and then converted to the desired format that throws a respective 3D program model, and 2) the thermoplastic material: which is a biodegradable plastic and mortar material [4]. However, the traditional way of building components consists of brick, concrete, steel, frame wood, and other materials.

3D printing is a sustainable method as it consists of 95-98% recycled materials. Also, it reduces the raw material to 75% by AM technology, energy consumption, as well as carbon dioxide. It is a patrol saving method because the material is light in weight [5]. On the contrary, the traditional building produces lots of waste due to fabrication finishing [5]. Moreover, concrete is not considered a sustainable material as it costs emissions [1] where other materials might be used for printing.

3D printing polymer for 1.67m with 97.59% positive proportion and 2.41% negative proportion. 3D-printed polymer-based formwork programming cost is 47.61\$/m^2, material cost is 204.93\$/m^2, and the machine cost is 451.05\$/m^2 which general cost is 733.53\$/m^2 [6]. The cost of the traditional building is expensive for small production as the cost is divided into casting molds, materials, manufacturing, and others [5].

Table 1. 3D printed concrete properties [2].

Bulk density of concrete in 3D printing		Flexural strength of concrete in 3D printing	
Extruded horizontal	2.053 kg/dm^3	Extruded horizontal	5.72 N/ mm^2
SC 3 horizontal	2.203 kg/dm^3	SC 3 horizontal	7.65 N/ mm^2
Extruded vertical	2.056 kg/dm^3	Extruded vertical	3.70 N/ mm^2
SC 3 vertical	2.172 kg/dm^3	SC 3 vertical	5.49 N/ mm^2
Compressive strength	58.10 N/ mm^2	Extruded vertical	59.5 N/ mm^2
SC 3 horizontal	71.10 N/ mm^2	SC 3 vertical	68.10 N/ mm^2

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In 3D printing, you can find a less negative impact with an increase in delay times. 3D-VtGW system decreases the heat in summer from exterior walls and it improves yearly thermal comfort [7].

Qatif population think that 3d printed house could be fabricated. But many questions related to this decision, how much will it cost compared with a traditional building? How can it affect the interior? How can it be repaired and maintained? The purpose of this research is to encourage the Qatif population to think about the other construction methods of building with low-cost benefits.

2. Method

To achieve the goal of this research, the data was collected in detail about traditional houses in Qatif and 3D printed houses in another region to provide a clear comparison that considers all the remarkable characteristics and factors.

2.1. Data analysis

Content analysis was used to analyze the data which was collected from other research papers and a live case study. This type of research where categorizing the data collected into characteristics to facilitate the comparison. The advantage of content analysis is the simplification it added along with the closeness it allows to the presented data. The categories used were the construction material, Cost, Energy spend, Execution time, and Sustainability.

2.2. Data collection method

For this research, search, thinking, and interviews were used as the data collection procedures. Interviews aimed at knowing participants' opinions and thoughts regarding the specific research subject. The advantage of conducting interviews was the ability to elaborate on interviewers' opinions. The interviews were structured to help in attaining comparable responses.

3. Results

3.1. Construction Method

3D printing has a special method in construction using Stereolithography technology, which is a technology that can build objects with high precision and extremely complicated geometry, that facilitates the repeatable production of elements with the help of a computer [4]. Also, using Fused Deposition Modelling (FDM), which is a process that contains a robot arm that has a nozzle, helps in keeping the filament at a good temperature to allow the mixture to flow smoothly to frame repeated layers one by one until the whole wall is constructed. This technique is only used in wall construction and for roofing, where the traditional method is used for the foundation [8]. Also, this technique is suitable for low-level buildings.

On the other hand, the traditional construction method used in building houses starts with the foundation. There are 3 types of foundation systems used in constructing houses as Basement: the deepest type, Crawlspace: foundation walls that stand on footings, and Concrete Slab-On-Grade: the slap of concrete that rests on the ground-level [9]. After that, start constructing the walls, and the most common system used in Qatif houses is the Reinforced Masonry Walls for the exterior wall, which used a reinforcing bar that placed in between the two-wall block.

Figure1. Concert 3D printing walls.

Figure2. Aldubaisi Fadhel house in Aljawharah, Tarout island, Qatif in process building, January 2019.

3.2. Construction Material

Nowadays, 3D printing machines have been developed to deal with different materials such as printing concrete which consists of a mixture of Sand, Cement, Fly ash, Silica fume, and Water. Typically, the powder consistency of stones and sand is the key to material processing. The powder uses chlorine-based liquids to work as a binder for printing complex 3D structures [10].

On the other hand, the traditional material used in constructing houses is the mixture of Portland cement, aggregate, water to form the brick, and the use of concrete and steel bars for the reinforced column [11]. After that, the mortar is applied to smoothen the wall surface, and between the bricks. And for the isolation, there are different materials used such as cellulose, natural fibers, fiberglass, and mineral wool, but the most common material used is the plastering board [12].

3.3. Sustainability aspects

The world now is giving a high value to sustainable designs in construction where 3D printing is achieving by adding a layer on top of the layer with exact and precise measurement to minimize the waste. Furthermore, it can decrease CO_2 emissions because the equipment does not need to travel long distances from the factory, instead, only one machine can do the whole process. Also, it can recycle different materials and convert them to a durable and flexible material [13].

3.4. Cost and Execution time

3D printing cost is more efficient than what people thought compared to the traditional construction as can be seen in table 2. Also, the table shows the execution time spends for all examples with this range of construction area, it will spend only 24 hours until the construction is done without the finishes.

Table 2. 3D printing average cost 3D Printed Homes | Apis Cor | United States (apis-cor.com) Our Story | ICON (iconbuild.com) About Winsun-Yingchuang Building Technique （Shanghai）Co.Ltd. (WinSun) (winsun3d.com)

House example (location)	Time of construction	Area m2	construction Cost	Average area	Average cost dollar
Apis Cor's House	24 h	410 ft^2	10150 $	١٢٩٧ft^2	8316.66$
ICON House (Texas)	24 h	500 ft^2	10000 $		
Winsun Houses (Shanghai)	24 h	10763 ft^2	4800 $		

3.5. Energy spends

One of the advantages of 3D printing is the reduction in the energy manpower spent on the construction site. Instead, two labor forces would be enough to control the whole operation, where one will keep tabs on the machine and the other will follow up with the computer control program [7].

On the other hand, the construction following the traditional way will need to consume a lot of manpower energy to build a house brick by brick manually, not to mention the amount of electricity used in the

site to do the construction. Also, the amount of waste in 3D printing could reach 0% and if there is any waste it will be recycled, wherein the traditional construction there is way more waste that is not recycled.

4. Discussion

4.1. Conventional method

4.1.1. Construction method

Figure3. Traditional built AlDubaisi house in Qatif, by researcher

Figure4. Foundation process, by researcher

Figure5. Wall system in process for roofing, by researcher

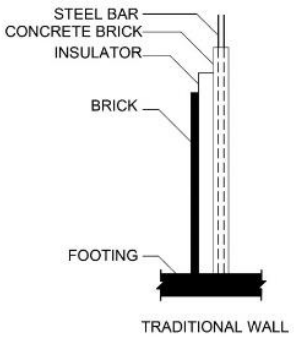

Figure6. traditional wall system, by researcher

Figure7. Frame wood for beams above the windows, by researcher

Figure8. Hidden beams from first floor, by researcher

AlDubaisi house in Qatif was selected as a case study for the traditional method. The land is good for building that it did not need drilling deep because it was 1m underground. It started with palm concrete with a depth of 0.10 m and is followed by a concrete area for footing with a depth of 0.4m, then the rectangular columns with fence columns 0.4*0.4 for bottom one and 0.4*0.2 middle and top one and the height of the columns was 3.8m. This type of column will support 418 m^2. As the living room was large, it was designed without having columns in the middle, instead, the cantilever was used in the ceiling which contains cantilever clear span, interior clear span, and then exterior clear span. For the walling system solid masonry walls were used which is a single wall that contains plain concrete, two steel bars 12mm vertically, two steel bars 12mm horizontally, and a lintel block.

4.1.2. Materials and cost

The house used different materials as they followed the traditional way of building. Reformed concrete which cost around 192.82 SR/ m^3 while it increased and decreased slightly around the year. As well as plain concrete which cost around 183.48 SR/ m^3. Rebar 16mm which cost 2501.97 SR/ ton with an increase and decrease around 120-190 SR/ ton. Isolated concrete blocks cost 2.50 SR/ block while concrete blocks cost 1.25 SR/ block. Cement cost 13.79 SR/kg and white soft sand cost 520 SR/ m^2 with a minor change. Electrical wires 2.5 mm cost 0.74 SR/m, 4mm cost 1.09 SR/m, and 6mm cost 1.69 SR/m with a stable price. Electrical cable 10mm cost 13.55 SR/m, 25mm cost 29.34 SR/m, and 35 mm cost 37.62 SR/m with minor increasing and decreasing. The total cost was 430,000 SR for the building materials.

Table 3. Conventional method material cost by researcher through interview

Material	Reformed concrete	Plain concrete	Rebar 16mm	Isolated concrete blocks	Concrete blocks	Cement
Cost	192.82 SR/ m^3	183.48 SR/ m^3	2501.97 SR/ ton	2.50 SR/ block	1.25 SR/ block	13.79 SR/kg
Material	White soft sand	Electrical wires 2.5 mm	Electrical wires 4 mm	Electrical wires 6 mm	Electrical wires 35 mm	total cost
Cost	520 SR/ m^2	0.74 SR/m	1.09 SR/m	29.34 SR/m	37.62 SR/m	430,000 SR / m^2

Machines were used such as cranes to lift and lower materials as well as to move them horizontally. An excavator which consists of a boom, dipper, bucket, and cab on a rotating platform was used in drilling. A Loader was used to move or load materials such as sand, or demolition debris. A dump truck was used to transport materials. A concrete mixer was also used to mix combines cement, aggregates such as sand or gravel, and water to form concrete homogeneously. A concrete pump was used to pump concrete from mixture to location. The total cost was 20,000 SR.

4.1.3. Sustainability

Due to the material used in the building process, it produced too many wastes as it filled 10 containers which also cost 50 SR per each. All the waste cannot be recycled or reused as its steel bars oxidate or when the block broke. In the plumbing and electrical process, more and more waste has been gained.

Figure 9. Aldubaisi Fadhel house in Aljawharah, Tarout island, Qatif. Under first stage process December, 2018

Figure10. Aldubaisi Fadhel house in Aljawharah, Tarout island, Qatif. Built structure in December, 2019

4.1.4. Execution Time

This kind of buildings needs so many different laborers ranging from workers who prepare the land and building the structure, electricians, plumbers, and drivers. Where all the building processes depend on them, how much they are efficient, and how many mistakes they might do. The owner needed to supervise the whole process of the building construction or otherwise assign it to someone else. The building started in December 2018 and ended in December 2019, where it took 12 months to build the structure. Concreate building structure starts with cleaning the land and drilling to reach a suitable layer. Then creating basement and ground beams. Next, build ground floor walls and ground slab. After that, build walls for the first floor and first slab. Lastly, build annexes walls and roof deck slab.

Table 4. summary of the cost and time taken for traditional house

	Material cost	Machan cost	Labor cost	General cost	Time is taken	Floors
Traditional way of building structure	430,000 SR	20,000 SR	250,000 SR	700,000 SR	12 months	2.5 floors

4.1.5. Energy spends

As it was manually built, it did not use much electricity, but it used too much petrol as many trucks were used. Also, it consumed much of the labor's energy.

4.2. Three Dimensional (3D) printed house simulation.

4.2.1 First 3D printing house simulation construction method

3D printing is done in a factory, not at the site. This differentiates Winsun's approach from other or ganisations. It is like the method of precast concrete construction, where factory-made components are transported to the site, lifted into place by cranes, and then connected together. A construction 3D printer is a machine that can build houses by depositing a material (concrete for example) layer by layer. Concrete 3D printing – a.k.a. "Construction 4.0" – is a similar 3D printing technology to the one that FFF 3D printers use. Paste-type material, in this case concrete or earth materials, is pushed through a nozzle in layers to print buildings in 3D. Concrete 3D printing in the construction industry helps save time, effort and material compared to traditional construction methods as shown in table 5. It is important to note, though, that 3D printers are not yet capable of creating a fully functional house. Only the frame and walls of the house are built; other elements, such as windows, electricity, or plumbing, need to be installed separately. But concrete 3D printers can also be used to print bridges, benches, or simply outdoor elements.

Table 5. The comparison between the traditional building and the construction using the 3D printer

	Traditional building	Construction using the 3D printer
Total area	418 m^2	418 m^2
Price per Squair metates	430,000 SR / m^2	2,951.37 SR/ m^2
Number of floors	2.5 floors	1 floor
Type of finishing	Plastering, painting	Painting
Energy consumption	manually built, few electricity, petrol, labor's energy	Machines, labor, programming
Time taken	12 months	24 hours
Number of regular and specialized employees	17 employees	6 employees

The land is good enough for building which does not cause them to drill deep it was 1m underground. It starts with palm concrete with depth of 0.10m and it is followed by concrete area for footing with depth of 0.4m, then the rectangular columns with fence columns 0.4*0.4 for bottom one, and for 0.4*0.2 middle and top one, and the height of the columns is 3.8m. This type of columns will support the same aforementioned area which is 418m^2. The living room is large and there is a need to design it without having columns in the middle, it uses a cantilever in the celling, which contains the cantilever clear span, interior clear span, and then exterior clear span. For walling system used solid masonry walls, which is a single wall, that contains plain concrete, two steel bars 12mm vertically, two steel bars 12mm horizontally, and lintel block.

4.2.2. 3D print house simulation Materials and cost

The materials used for 3D printing are as diverse as the products that result from the process. As such, 3D printing is flexible enough to allow manufacturers to determine the shape, texture, and strength of a product. Best of all, these qualities can be achieved with far fewer steps than what is typically required in traditional means of production. Printable concrete mortar costs 196.58 SR/m^2. Rebar 16mm which cost 2501.97 SR/ ton. Reformed concrete which cost around 185 SR/ m^2. Insulator which cost 60 SR/ m^3.

Table 6. 3D printed method material cost by researcher through interview and 3D Printing Service Marketplace | Craftcloud® by All3DP (craftcloud3d.com)

Material	Printable concrete mortar	Rebar 16mm	Reformed concrete	Insulator	Total cost
Costs	196.58 SR/ m^2	2501.97 SR/ ton	192.82 SR/ m^2	60 SR/ m^3	2,951.37 SR/ m^2

4.2.3. 3D printed house simulation Sustainability

One of the most important contributions that 3-D printing can offer to the sustainable construction movement is the reduction of waste. After designing a home on a computer, a 3-D printer will know the exact number of materials needed for the construction of the home.

more efficient fabrication techniques have tremendous potential to reduce scrap, reduce material transport costs, improve building lifespans, and reduce the total operating costs. There is very little innovation in building methods in residential construction where 3-D printing stands to make early and rapid inroads. By limiting construction waste and material transport costs, 3-D printers have the ability to drastically reduce the carbon footprint associated with building homes. Furthermore, 3-D printers can be developed to make homes out of sustainable and renewable materials.

4.2.4. 3D printed house simulation Time

In this kind of buildings, no need for many labors to work in preparing the land and building the structure, electrician, plumber, and drivers. Then the average price of labor is 112.29 SR/m^2. The labor number is decrease in 3D printing than traditional home which needs more labor number which affects the time needed.

Table 7. summary of the cost taken for 3D printed house

	Material cost	Machine cost	Labor cost	General cost	Time taken	Programming cost
3D-printed	2,951.37 SR/ m^2	1691.72 (SR/m^2)	112.29 (SR/m^2)	2751.20 (SR/m^2)	24 hours	178.57 (SR/m^2)

4.2.5. 3D print house simulation energy spends:

As it is not manually built house it uses much electricity, also, it uses less of labor energy where all the efforts are on them in the conviction way as shown in table 5.

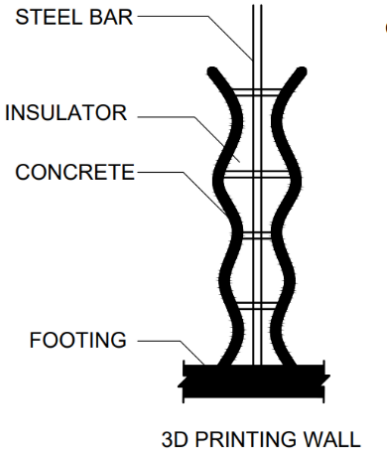

Figure11. 3D printing wall system, by researcher

4.3. Recommendation

The outcomes from the comparison of the advantages and disadvantages of 3D printing and the traditional way will be summarized below.

To compare both methods when it comes to the cost of the materials used in building, the traditional way consumed more materials than 3D printing. Consequently, 3D printing has saved 123,000 SR.

The need for machines in the traditional building costs a fortune when compared to 3D printing which saves up to 778,191.2 SR. For the labor force, the 3D printed building needed less labor which effectively cost less than a concrete building. When it comes to time consumption, 3D printing took less time than traditional building as it can work longer hours and faster with a stable amount. Furthermore, 3D printing saved a lot of energy spent in construction, as opposed to the traditional way of construction where it required more people to work on the site to make a progress and build the house in the specific time frame. Lastly, the safety aspect and risk-management play the biggest disadvantage of the traditional way of leaving 3D printing as the best choice to be adopted in this light.

4.4. Conclusion/Limitation

To make a sustainable design, the paper focuses on the advantages of 3D printed houses in the cost, the time of construction, labor cost, waste of building materials is low compared to building used traditional method. In fact, 3D printed houses planed and studded very well at the beginning which so, it avoids waste related to interior finishes such as plumbing, electrical, air conditioning, wall and ceiling cladding, and they are produced waste. The reason for this is the accuracy and advance planning of construction details in advance. The research study did not mansion how these problems were solved in 3D construction. 3D printing has a special method in construction that used Stereolithography technology which is a technology that can build objects with a high precision and extremely complicated geometry, it is a repeatable production of elements with the help of computer. 3D printing of radioactive phantoms using 99mTc-containing building materials is feasible. Compared to the classical fillable phantoms, 3D printing with radioactive building materials allows manufacturing of phantoms without cold walls and in almost any shape. Related procedures with longer-lived radionuclides will enable production of phantoms for scanner validation and quality control.

It was very hard work due to unavailable labs to do further experiments and to test buildings from different aspects. Testing the soil and the weather in the real site is also a further study that can be handled in the future. Hopefully in the upcoming to complete the step for different cities and under various conditions.

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