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Analytical Study for Sustainable Solutions of 3D Printing in the Construction Industry Challenges

(3D printing technology current practices and applications)

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Abstract: The world has witnessed a rapid increase in human activities. Humans interactions and responses to challenges in the built environment to make a place to live. As society grew, new technologies and methods are needed to sub-stand living conditions. construction industry faces many challenges in the built environment reflected in low productivity growth due to minimum technological advances for decades. One of the approaches for solving these challenges is shifting towards automated construction industry using 3D printing technology. This paper aims to provide an analytical study for sustainable solutions of 3D printing in the construction industry challenges. A literature review has been done to analyze 3D printing technology, its processes and advantages it provides. followed by a qualitative study for 3D printing in multiple applications. findings of this paper are valuable as a guideline for architects and engineers when taking a decision in the beginning of a design process when selecting which technology to use.

Keywords: Additive manufacturing, 3D printing, automated construction industry, sustainability

1. INTRODUCTION

Construction is one of the world's major industries. The engineering and construction business accounts for around 6% of worldwide GDP (gross domestic product) and generates roughly $10 trillion in yearly revenues [1]. Having made significant economical contributions, however, many studies have shown over the years the construction sector is still facing many challenges resulting from consumption of raw materials, poor productivity, limited technical improvements, minimal automation, and robotic utilization [1]. as shown in figure.

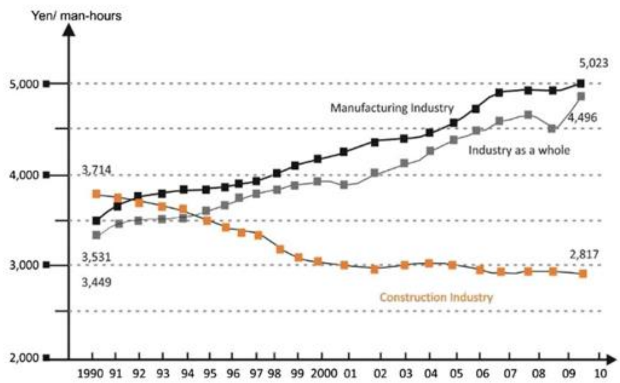


Fig 1. productivity of construction industry in contrast to manufacturing industry [2].

According to [3], it was suggested to introduce innovative materials, enhanced automation, and digital technologies. Additive manufacturing (AM) which is frequently referred to 3D printing, is among the most recent technological innovations that has been introduced in the construction sector which could be regarded as one of the key drives behind the sector's shift to digitalization as shown in Figure 2.

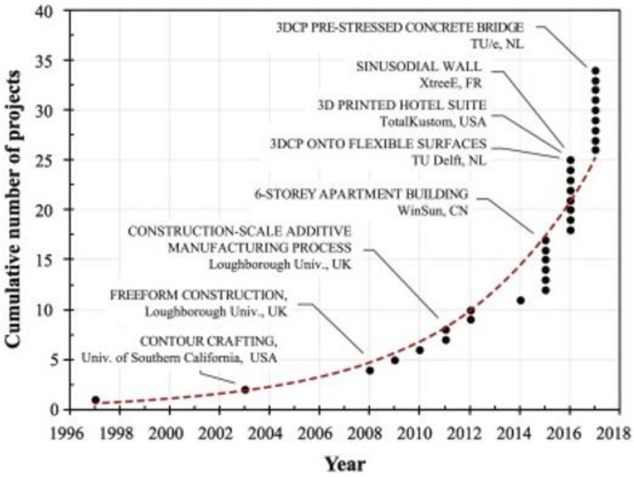


Fig 2. Large-scale additive manufacturing's growth in the construction industry since the concept's introduction in 1997 [4].

2.Materials and methods

This section outlines the hierarchical approach process of the methodology used in this work is presented. since the qualitative technique relies on tracking down recent research, surveys, commercial solutions, and attempting to expand upon already conducted studies, it is the most suitable approach for this particular topic. In order to develop optimum solutions of 3D printing applications in construction industry challenges and set as a guideline for architects and engineers when taking a decision in construction.

- Identifying 3D printing definition and current construction shifting towards automated industry, 3D printing techniques and 3D printers used.
- Analytical study for 3D printing multi sustainable solutions in construction.
- Developing a conceptual work flow to follow to choose optimum solution for construction situation case.

3 Literature Review

Accordingly, the following paragraphs provides the literature review for current construction industry challenges that faces. Then identifying 3D printing technology, its techniques and multiple applications in construction sector.

3.1 Current construction industry

The basic ideas of construction remain unchanged for hundreds of years; concrete was created by the romans in 100 BC, and 2200 years later, we are still utilizing it as our main building material and (mostly) manually placing the components. Like any industry, there are difficulties in this business, just as in any other. The issues facing the construction industry have long been known, and they include working in hazardous conditions, losing workers with the necessary skills, decreasing productivity, maintaining worker safety, generating a lot of waste material, and transporting supplies to the building site. Furthermore, this industry consumes a significant amount of resources, roughly 50% of all raw material consumption and 36% of all final energy use worldwide [4].

3.2 Definition of 3D printing

Additive manufacturing (AM) is a process that enables 3D designs to be produced directly from CAD files without the need for specialized equipment or dies. Multiple layers are formed in the x-y direction on top of one another in this freeform layer-wise fabrication to create the third dimension, or z. once the component is constructed, it can be tested to create working prototypes [5]. "According to American society for testing and materials (ASTM) international technical committee, additive manufacturing (AM) refers to methods that sequentially join material to make physical objects based on 3d Model data, usually layer by layer in contrast to subtractive manufacturing processes [6]. A comparison between two processes is illustrated in Figure 3.

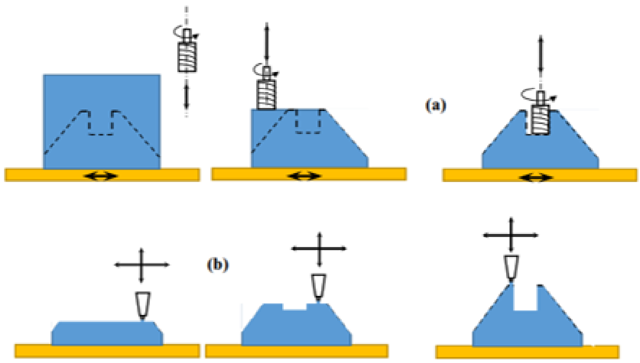
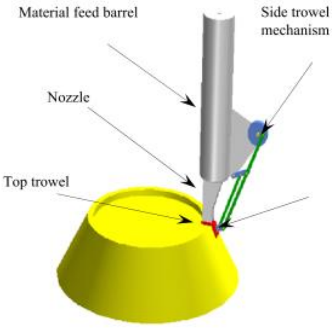
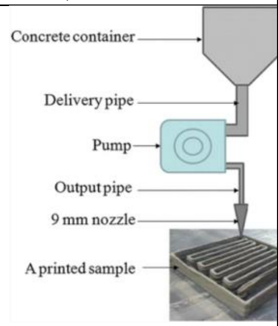


Fig 3. Comparison between a classical subtractive manufacturing and b AM [7].

3.3 AM large scale techniques in construction

For large scale construction projects, according to [8]. Various 3DCP technologies have been developed in recent years to enable the use of AM in concrete building an illustration conducted by authors is shown in figure 4. These technologies are primarily based on two techniques: extrusion and powder. contour crafting and concrete printing are extrusion-based methods that apply the theory of fused deposition modelling, but D-shape is a powder-based process that uses a distinct principle called stereo-lithography [9].

Table 1. summary of 3D printing techniques

3D Printing large scale techniques	contour crafting	concrete printing (Free-form)	D-Shape	source
Description	CC is an additive manufacturing extrusion based process that combines computer control to take advantage of troweling's outstanding surface-forming capacity to produce smooth and precise planar and free-form surfaces[8].	Concrete printing additive extrusion process using layer by layer. it achieves superior control over complex designs due to its lower deposition resolution [9].	The D-shape process is Injecting a binder into the material layer. the approach employs a powder deposition process [10].	[10], [11], [12]
Machine	Gantry system	Concrete 3D printer	D-shape 3D printer	[13]
Production process	Extrusion process (layer by layer)	Extrusion process (layer by layer)	Binder jetting (deposing)	[13]
Material	Cementitious material	High-performance concrete, cement mixture	Powder bases	[13]
Structure	Concrete buildings, houses (printing in mega-scale)	Concrete structures (limited printing by frame)	Architectural artifacts	[13]
	 **Figure 5.** contour crafting process [10].	 **Figure 6.** schematic of concrete delivery system [14].	 **Figure 7.** Andrea Morgante created Radiolaria, with D-shape [12].	[10], [14], [12]

3.4 3D Printing large scale Equipments

There are several 3D printing machines focused on the production of construction components. Each machine has advantages and disadvantages, such as the printing area, equipment weight, and shipping and assembly processes [16]. A schematic illustration of the two primary motion controllers for 3D printing, based on the gantry and robotic arm systems shown in Figure 8.

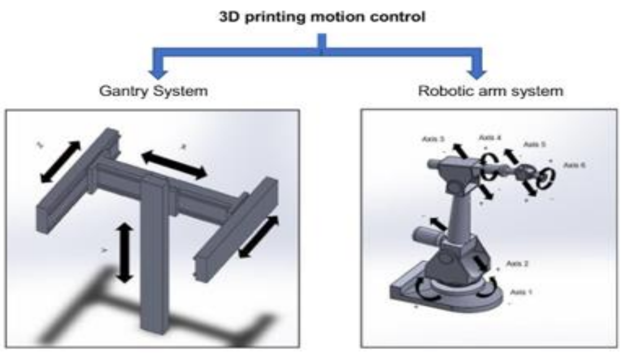


Fig 8. 3D Printing motion control [15].

3.4.1 Gantry system solutions

Another name for a gantry robot is a cartesian or linear robot. Its benefits include easy computations, natural spatial expression, increased precision, and wide applicability. Any point in the three-axis space region may be precisely located by linear movement on the x, y, and z axes since it has servo motors in the x, y, and z axes, respectively. The three axes' movement ranges define the printing size. thus large-scale gantry robots might be used on an architectural project [17]. Figure 9. shows gantry system components.

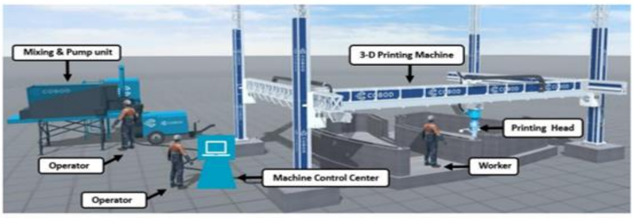


Fig 9. Gantry printer system components [16]

Concrete printing, contour crafting and D-shape are the two most well-known uses of gantry printers. Layer-by-layer extrusion is the mechanism used by these printers [16].

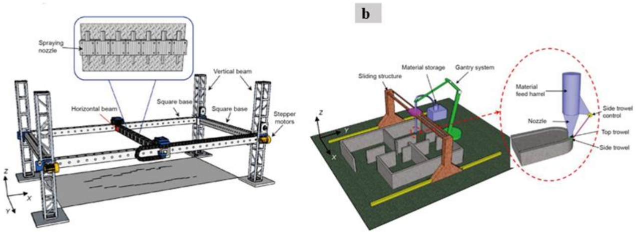


Fig 10. (a) schematic representation for D-Shape printer [11]. (b) Building construction using contour crafting printing technique [11].

3.3.1 Robotic arm printer

The way the robot's big and little arms swing is transmitted is comparable to how the human body's elbow and shoulder joints move, which typically have three to seven degrees of freedom [17]. when compared to gantry printers, the robotic arm system is relatively recent. using the tangential continuity approach (defined as creation of layers of different thickness to optimize the structure being built, these layers have a large surface area of contact with each other), such a technology allows for the printing of more precise and detailed items. Tangential continuity enables a smoother transition between print layers by keeping a consistent rate of change in curvature, resulting in a more attractive look [18].

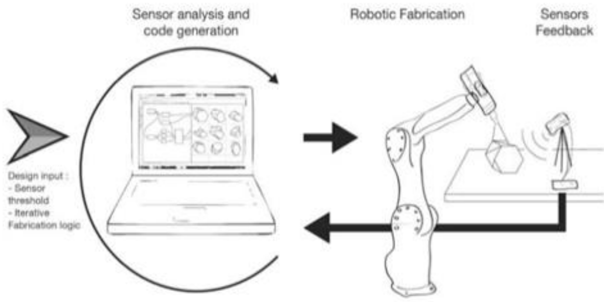


Fig12. robotic arm work flow [19].

Table 2. summary of 3D printing machines for construction

3D Printing Machines	Gantry-Systems	Robotic Arm systems	Source
3D Printing methods used	contour crafting, concrete printing, D-shape	contour crafting	
Degree of freedom	3 (x,y,z) axis	6 axis	[17]
Advantages	Printers use rails, gantry, wheels and caterpillars Simple to use • High precision • Produce large scale prints • Increased size of print area	• Printers using a robotic arm rotating 360 degrees. • Simple to operate, easy to control due to advanced software • More accurate and detailed objects • Tangential continuity method • Flexible mobility	[18], [17]
Disadvantages	• Complex, quite large and heavy • Limited mobility • Need assembly/ disassembly at each construction site • Limited ability to create complicated and detailed geometries	• Restricted print head height and printer size • Limited size of printable objects • Small printed area • Limited materials only fine aggregate	[18]

4. 3D printing applications in construction industry

3D printing technology applications in architecture have advanced from scale modelling to a completed full-size product. In the construction business, it will have several applications on a large scale including commercial, industrial, public, and private sectors. bridges, civil infrastructure, and artworks have all been created using construction 3D printing technology. It can also allow building to take place in harsh or risky settings where human work is not appropriate, as in military cases. these technologies have the potential to result in faster construction, lower labor costs, increased complexity and accuracy, more function integration, and reduced waste [20]. An illustration of these 3D printing applications are illustrated in Figure 13 "conducted by the authors".

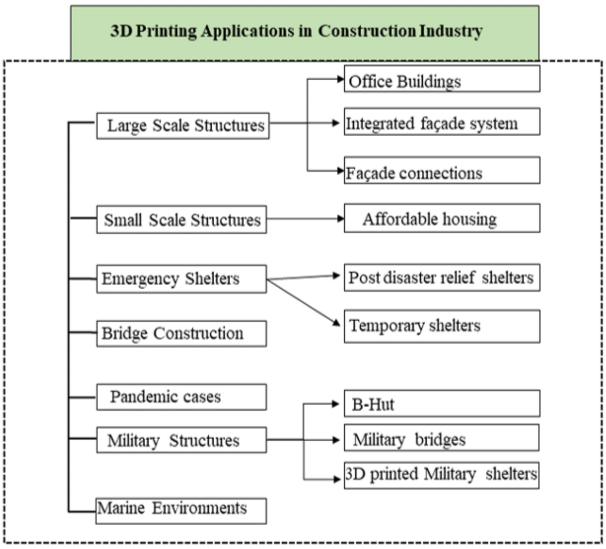


Fig 13. summary of 3D printing multiple applications in construction industry [20] " adapted after"

4.1 office buildings

Apis Cor's office building is the tallest 3D-printed building in the world to date in Dubai. The structure was constructed far more quickly than a conventional construction project, particularly the two-week-long on-site 3D-printed components. The printing was finished on-site to demonstrate that the technology could tolerate a harsh environment without humidity or temperature control [21].

Fig 14. world's largest 3d printed office in Dubai [21].

4.2 Integrated façade system

Present facades are being reevaluated to achieve high levels of usefulness and efficiency. Because conventional facades have uniform and standardized characteristics, which restrict both their recyclability and their capacity to be customized to their unique environmental circumstances [22]. The goal is to create integrated building components that are suited to the site, orientation, usage, and services of the building. A major shift towards site-specific facades. This progress can be accelerated by 3D printing, as it makes it possible to create custom, multipurpose pieces in a building made of a single material, as shown in Figure 15 [22].

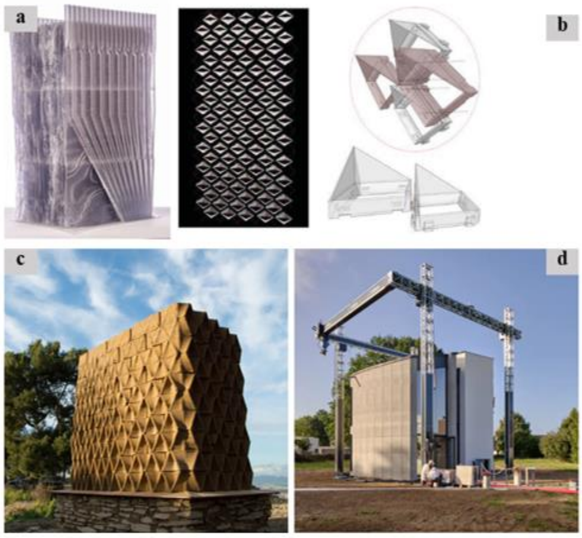


Fig 15. (a) sponge 3D façade (Adaptive façade system for thermal performance) [22], (b) 3D printed panel module for sun shading façade system [21], (c) terraperforma 3D printed modular clay wall [23], (d) 3D printed concrete façade house by Kamp C [22].

4.3 3D printing for façade nodes and connections

Façade nodes frequently have complex geometries to satisfy a range of performance requirements. The Nematox façade node was created to demonstrate how additive manufacturing techniques can be applied to provide more optimal façade shapes with room for increased creativity and geometric flexibility, as seen in Figure 16. The suggested approach relocates the structural connections outside the node. limiting the possibility of flaws impacting the environmental sealing [24].

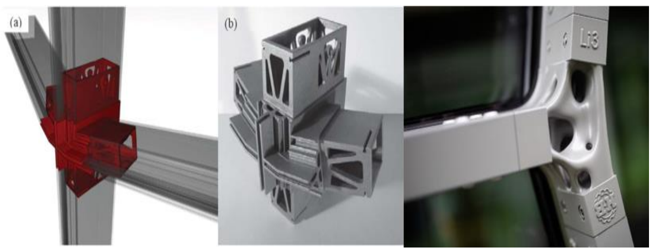


Fig 16. a full-size aluminum prototype node of a Nematox façade node (a, b) [24] (c) Li3designers façade connection [25].

4.4 3D printing for affordable housing

The need for affordable housing has increased over the past several decades, with developing nations focusing on raising the living conditions of lower- and middle-class people. The need for affordable housing is also a result of urban migration and population expansion. Furthermore, with the economic uncertainty and downsizing induced by the COVID-19 epidemic, lower and moderate income households are further financially stressed by salary cuts and unemployment. In order to achieve the required standards of affordability, digital fabrication can be used to create cost-effective building methods, as shown in Figure 17 [26].

Table 3. A summary of some existed 3D Printed affordable housing projects are illustrated.

	No	Projects	Project description	year	location	Method/Material	Source
3D Affordable housing	1	Mense-Korte	- two-story house with area 80m2.	2021	Germany	On site gantry system with concrete material.	[27]
	2	Project milestone.	- consists of 5 3D printed residential houses. -1,011 square-foot (94m2) dwellings.	2021	Eindhoven, Netherlands	On-site 3D concrete printing	[28]
	3	Chicon house	-1 storey building with area 350 square feet.	2018	Austin, texas	On-site concrete extrusion using gantry system.	[29]
	4	Biohome3D	-1 storey with area 600-square-foot.	2021	Orono, Maine, United States	Extrusion Concrete printing	[30]

Fig 17 (a) Mense-korte's Germany 3D printed house [27]. (b) Milestone 3d printed house [28], (c) Chicon house, ICON's 3D Printed House in Texas [29]. (d) The first bio-based 3D-printed home in the world, biohome3D [30].

4.5 Emergency housing solutions / Post-disaster housing/ shelters

Following a natural disaster or complex emergency, people responding must establish a supply network to ensure that the goods and services required to meet the requirements of the impacted population are supplied as efficiently and effectively as possible [29]. The requirement for temporary housing (TH) and shelters (TS) is the main issue that requires urgent attention [31]. Using three-dimensional printing (3DP) technology is one such new option that can be able to produce a specific piece of equipment (such as a spare part) in a location near the affected region. In doing so, it would achieve improved efficiency through the transportation of a base material that can subsequently be used to manufacture a broad range of finished goods to meet an identified need, and it would also avoid the delay inherent in obtaining the required item from a distant location [32].

Fig 18. 3D printed shelters for homeless [32].

4.6 3D printing for bridge construction

While C3DP technology has helped with emergency shelters and affordable homes, employing C3DP for infrastructure development appears to have a lot of promise as well. This automated and quicker process has promise for civil constructions like buildings and bridges, which require significant labor [33].

Table 4. A summary of some existed 3D Printed bridges projects are illustrated.

3D Printed Bridges	No	Projects	Project description	year	location	Method/Material	Source
	1	3DCP bicycle bridge	-6.5m span -3.5 width	2017	Gemert village in Netherland	off-site Extrusion Robotic arm	[33]
	2	MX3D Bridge	-12 m span -6 ton stainless steel structure	2021	Amsterdam, Netherlands	off-site fabricated	[34]
	3	Castilla-La Mancha 3D Bridge	-12m span, width 1.75m. -1.3 m high handrail	2016	Madrid, Spain	off-site fabricated	[33]
	4	China's Netflix 3D printed pedestrian bridge	-26.3 m long -3.6m wide	2019	Shanghai	off-site fabricated	[33]

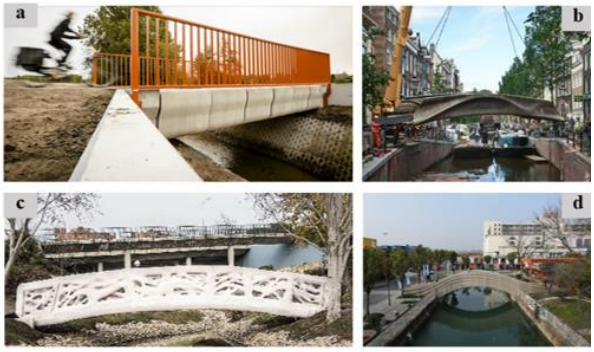


Fig 19. (a) concrete 3d printed bicycle bridge [33]. (b) World's first 3D printed steel structure [34], (c) Castilla-La Mancha 3D bridge [33], (d) 3D printed pedestrian bridge in china [33].

4.7 3D printing for harsh military environments

The Automated Construction of Expeditionary Structures (ACES) program was launched in 2015 by the United States Army Corps of Engineers' Engineer Research and Development Centre Construction Engineering Research Laboratory (ERDC-CERL) in order to develop dependable, user-friendly 3D printing technology that can produce specially designed military expeditionary structures on-demand in the field using locally available materials [35].

Table 5. A Summary of some existed 3D Printed military projects are illustrated.

3D Printed Military Structures	No	Projects	Project description	year	location	Method/Material	Source
	1	B-Hut	16' x 32' x 9.25' print in 48-hours	2017	champaign,Illinois in united states	Concrete material	[36]
	2	Military pedestrian bridge	10 meters (33ft) long	2018	-	on-site concrete structure	[37]
	3	3D printed bunkers (shelters)	Weighs 40kg	2018	-	on-site Drying concrete and admixtures	[37]
	4	Vehicle hide structure	26' L x 13' W x 15' H	2018	-	off-site cement-based material called Lavacrete	[37]

Fig 20. (a) 3D Printed Barracks hut [36], (b) the 3D printed pedestrian bridge [37], (c) 3D printed bunker [37], (d) vehicle 3d printed hide truck [37].

4.8 3D Printing for space settlements

A prime example of an isolated environment is space, which is geographically isolated and lacks access to labor, supplies and machinery. It also lacks a well established construction industry and process built in construction industry and process, as well as experiencing harsh weather conditions such as high radiation, extreme temperatures, dust storms, and earthquakes [35]. Future space habitat construction must be able to safeguard its occupants and provide useable areas for living and working, much like their counterparts on Earth. [38].

Together, Made In Space, Inc. (MIS) and the National Aeronautics and Space Administration (NASA) have created archinaut, a cutting-edge platform for additive manufacturing and assembly in space illustrated in Figure 21. Building on a foundation of technical and logistical expertise gained while running the MIS Additive Manufacturing Facility (AMF) on the International Space Station (ISS) [39].

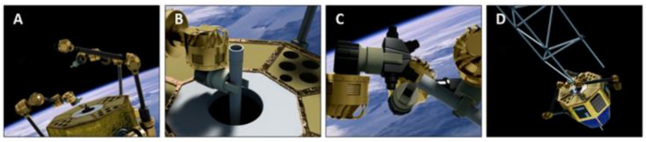


Fig 21. (A) Archinaut makes nodes and (B) struts, (C) Archinaut's robotic manipulators work together to mate structural parts, and (D) Archinaut autonomously assembles structural elements into a truss [39].

4.9 3D printing in pandemic cases

The pandemics such as COVID-19 have had an influence on practically every area of human civilization, both collectively and individually, from professional to personal [40]. The engineering and construction industry is the most severely impacted sector by pandemics. The sector has already had to deal with a number of difficulties, including a shortage of funding and a number of environmental laws' regulations (Regulation and Development) [41]. The mobility of people and groups was strictly restricted. However, all building and the majority of commercial activity nationwide have stopped as a result of the government's limitations [41].

Today, automated construction employing 3DCP can offer a safer, more dependable, more productive workplace, more regulated working environment than traditional construction sites, with static workstations and systematic monitoring, quicker construction timeframes and cheaper labor costs, as well as the use of more ecologically friendly raw materials. 3D printing has been utilized to create temporary emergency shelters to segregate people in quarantine, alleviating the burden on hospital infrastructures, as shown in Figure 22. 3D-printed homes are also lightweight and portable, making them ideal for deployment in remote places [42].

Fig 22. 3D printed Isolation awards [43].

3D printing for marine and urban environments

Concrete is the most widely utilized material in buildings. The durability of concrete has gained significant significance in recent decades. All concrete constructions deteriorate, regardless of how well they were designed and built. This phenomenon has become clear and concerning for many modern constructions in marine environments that exhibit severe and early degradation as well as limited durability. Corrosion is the primary cause of deterioration to reinforced concrete (RC) structures. This process reduces the load capacity of the structures, hence affecting structural safety. Therefore, current 3D concrete printing technology to overcome these limitations, as shown in Figure 23 [44].

Fig 23. (a) cosmic 3D printed hotel [44] (b) Kisawa sanctuary 3D printed resort (c) adaptive urban coastline concrete structure [44].

5. Summary

In sum, according to above mentioned multiple applications of 3D printing in the construction industry challenges. It was found that some construction structures its optimum solution should be fully constructed using 3D printing technology due to their harsh circumstances, high hazard environment, difficulty for accessing of labors and transportation to the environments they face and the need for fast track construction such as emergency cases, post-disaster relief, harsh environments, etc. Other structures either they are already existed or newly constructed to build, can be constructed using integration of both 3D printing method and conventional method. At which a range of components of building can be prefabricated off-site or printed on-site. Figure 24, is a proposed conceptual work flow for choosing 3D printing optimum solutions in construction challenge cases.

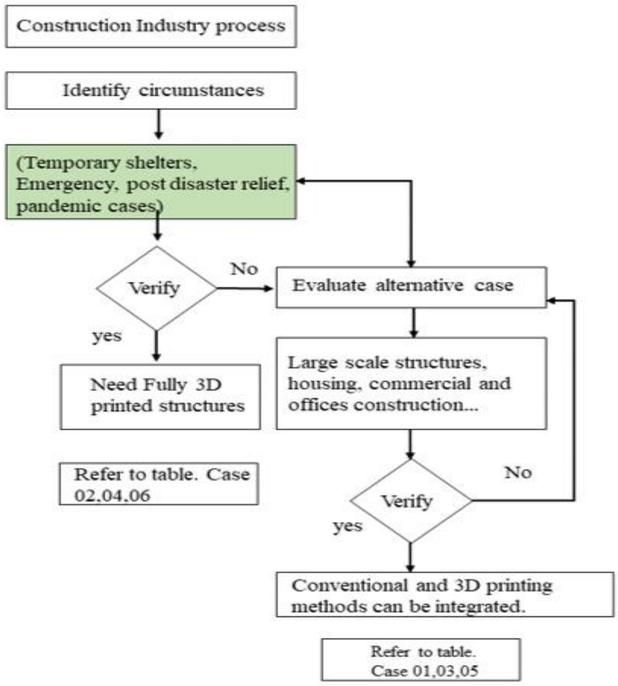


Fig 24. Conceptual flow chart for choosing optimum solution in construction according to circumstances found, conducted by authors.

Table 6. Construction industry challenges optimum solutions with 3D printing.

Cases	3D printing process	Integration of 3D printing with conventional process	optimum solution
01-High-rise buildings	-	✓	Integration of both 3D printing and Conventional method.
02-Emergency shelters, pandemic isolation	✓		3D printing of whole structure.
03-Affordable housing	✓		3D printing of whole structure.
04-Bridge construction	✓		3D printing of whole structure.
05-commercial and offices		✓	Integration of both 3D printing and conventional method.
06-space settlements	✓		3D printing of whole structure.
07-marine environments	✓		3D printing of whole structure.

4. Conclusion

This research confirmed that 3D printing technology is an optimum solution for construction industry challenges. Shifting to automated construction results in revolutionizing productivity in construction, offering more efficiency, more freedom and a reduction in time and cost.

- on the other hand, this study provided qualitative information for multiple uses of 3D printing technology as an optimum alternative solution to conventional methods for many challenges that face the construction industry.

-Therefore, this paper might be useful as a guideline for architects and engineers when taking a decision in the beginning of a design process when selecting which technology to use.

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