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Exploring 3D Printing Potentials for Sustainable, Resilient, and Affordable Housing

Benjamin Everett[1], Julian Soto[2], Payam Bakhshi[3] and Afshin Pourmokhtarian[4]

[1] *Wentworth Institute of Technology, Boston, MA, U.S., everettb@wit.edu*
[2] *Wentworth Institute of Technology, Boston, MA, U.S., sotoj5@wit.edu*
[3] *Wentworth Institute of Technology, Boston, MA, U.S., bakhship@wit.edu*
[4] *Wentworth Institute of Technology, Boston, MA, U.S., pourmokhtariana@wit.edu*

Abstract

The construction industry showed remarkable resiliency during the global pandemic, and it is a worldwide engine for economic growth. However, many construction companies are predominantly building with traditional techniques and have not adapted to utilize available technological advancements. Therefore, industry is behind the curve to address global issues such as combating climate change and providing more affordable housing. Thus, it is necessary to continue the exploration of options to utilize available technologies that offer innovative solutions to today's global challenges and pivot toward a more sustainable and inclusive future. Nowadays, 3D printing is one of the fastest-growing technologies in construction. This building method could provide answers to the above-mentioned issues and open new and exciting opportunities for the construction industry. This paper will examine how 3D printing can contribute to solving the needs for more sustainable, resilient, and affordable housing. The technology of 3D printing is explained, focusing on the use of 3D printing of structures for housing construction. Once the technology behind 3D printed houses is conveyed, the sustainability and cost benefit analysis of this construction method are explored and compared with traditional construction techniques. The sustainability aspect is explored through analyzing and comparing other similar sized traditionally built homes. Similarly, the affordability of this construction method is compared with current techniques to determine the benefits of this type of construction. Upon the conclusion of the work, a clear pathway is provided on how to utilize 3D printing in constructing more sustainable, resilient, and affordable housing for the future.

Keywords: Construction, 3D printed houses, sustainability, resiliency, affordability.

1. Introduction

1.1. 3D printing technology

Additive fabrication or 3D printing is a technology that is reshaping the manufacturing and building industries. This construction method can be defined as the automated process of adding materials to build objects or structures using digital data made by Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM). The construction process consists of developing a digital model that will be divided into a series of layers. After that, a 3D printing machine will deposit material layer by layer, as each successive layer bonds with the previous one until the object or structure is complete. 3D printing process is depicted in Fig. 1.

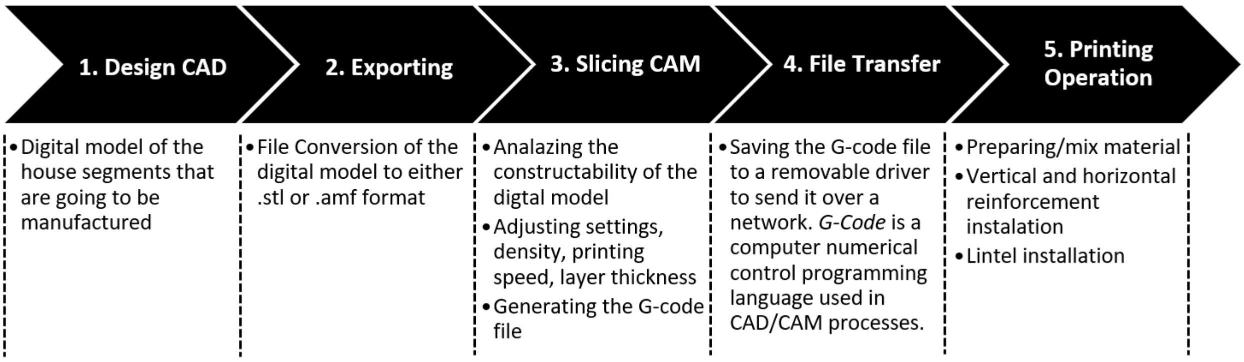

Fig 1. An illustration of 3D printing process

1.2. 3D printing in the construction industry

Since the moment of its invention, 3D printing has targeted the manufacturing sector. This technology has been used to develop prototypes with low manufacturing volumes, objects with small dimensions, and products with complex designs [1]. However, over the years, this technology has been expanded for use in projects related to the architectural, engineering, and construction (AEC) industry. The following three areas have used 3D printing in projects related to the AEC industry: (1) the development of small-scale products that are installed in structures, (2) the manufacturing of architectural scale models, and (3) the construction of building elements.

The first way to use 3D printing technology in the manufacturing sector is to produce objects that are part of a given building. For example, [2] explored the practical adoption of 3D printing for creating an electronic switch knob from a digital model. Later in 2016, Wu et al. [1] described how 3D printers could employ materials such as plastic and nylon. These materials are commonly used to produce small building devices, including plug fixtures, window frame fittings, and plumbing fittings. Recently, Branch Technology [3], focused on the manufacturing of panels and facade systems that are stronger and lighter with a variety of designs. Thus, the AEC industry has the potential of utilizing 3D printing to make small and medium-scale products for the construction process.

The second way to use 3D printing is in projects related to manufacturing architectural scale models. Model makers have been vital to exploring and testing architectural and infrastructure projects before starting construction. While technical tools and manufacturing methods have evolved, the fundamental role of a physical model, to explore and analyse ideas in three-dimensional form, has endured [4]. In the initial stages of the design process, scale models are built to conduct volumetric, energy, and strength analyses. One of the advantages that technology offers is the reproduction scale of both complicated and straightforward geometric shapes within hours. Therefore, the AEC industry has embraced this technology to create scale models since the early 2000s [1].

Finally, the third use of this technology is connected to the automated manufacturing of large-scale building elements. One of the innovations in 3D printing is the Contour Crafting (CC) layer manufacturing process, developed in 1998 by Dr. Behrokh Khoshnevis, professor at the University of Southern California (USC) and researcher in robotics. CC is a 3D printing technology that uses CAD and CAM to create various surface shapes, using fewer trowelling tools than traditional plaster handwork and sculpting [5]. This printing methodology is used to manufacture building components such as internal and external walls or structural elements, including columns and beams. Buildings that have been benefiting from this technology have typically focused on the automated manufacturing of exterior and interior walls which mimics the concrete masonry unit (CMU) construction process. Fig. 2 provides a comparison between traditional CMU and 3D concrete printed walls.

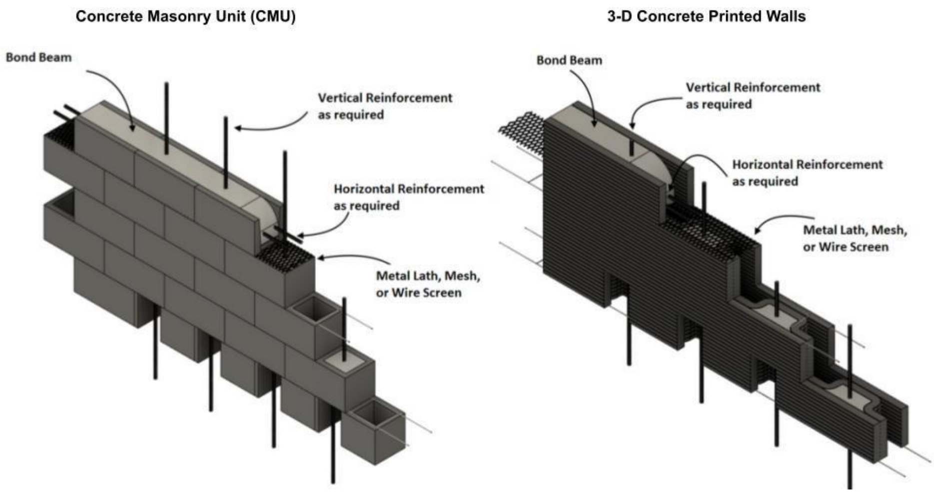

Fig. 2. Comparison between traditional CMU and 3D concrete printed walls [6]

Since the printed material acts as a mold, one of the advantages of CC technology is the elimination of formwork for cast-in-place concrete. Local casting has been used inside 3D printed walls around manually installed steel reinforcement bars by Apis Cor [6]. Thus, it is possible to add vertical and horizontal reinforcements during the printing process. Additionally, walls built using this technology can have different finishes and insulation between layers. Fig. 3 shows the details of a 3D printed wall.

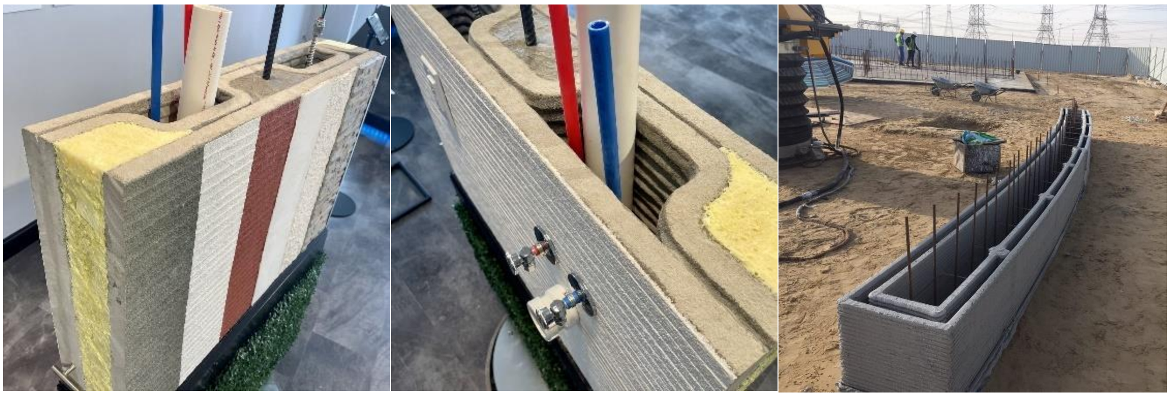

Fig. 3. Details of a 3D printed wall by Apis Cor [6]

1.3. Construction 3D printer machine types

There are different 3D printing machines focused on manufacturing of building elements. Companies and universities worldwide have developed various devices, including (1) the Robotic Arm, (2) the Telescopic Arm, (3) the Gantry System, and (4) the Modular Crane, just to name a few. Each machine has advantages and disadvantages, such as the printable area, the weight of the equipment, and its transportation and assembly processes. For example, as COBOD [7] states, the advantages of robotic printers are their easy transportation and versatility to print individual elements with high complexity. That is due to the 6-axis movement of these machines. However, one of the disadvantages of robotic printers is the limited printable area. Users of robot printers are virtually forced to print components rather than whole structures or buildings. The robot is large, the arm is short, with a maximum reach of three meters, which is typical of robot printers, and it requires a lot of free space [8]. This feature can limit the printable area considerably. Thus, this machine is not ideal for printing the entire building elements or large structures.

On the other hand, gantry printers can do larger-scale prints continuously. Additionally, this type of machine is easy to control and does not require highly skilled programmers [8]. One of the disadvantages of gantry printers is their low flexibility for printing complex and detailed geometries. That is due to the 3-axis movement of this machine. Nowadays, companies typically develop their own software for importing 3D models, performing the slicing process, and converting the 3D geometry to G-Code. Table 1 shows devices developed for 3D printing in construction with advantages and disadvantages of each.

Table 1. Construction 3D printer machine types

Machine Type	Advantages	Disadvantages
Robotic Arm	Transportability and versatility in printing individual elements of high geometry complexity.	This machine has a limited printable area. The robot cannot print large structures. Additionally, the machine requires highly skilled programmers.
Telescopic Arm	This type of machine can manufacture larger-scale walls continuously. Furthermore, due to its light weight, it can be easily transported and placed in different site work areas.	Medium-low precision in printing elements with high geometry complexity.
Gantry System	This type of machine is easy to control and does not require highly skilled programmers. Printing with a gantry printer lets operators control the material flow. Moreover, the gantry system can manufacture small and large-scale walls continuously.	Medium-low precision in printing elements with high geometry complexity. The transportation and assembly processes could take more time and be more complex. For example, the transportation and assembly of the COBOD machine could take approximately two days.
Modular Crane	Due to its modular design, this type of machine can manufacture larger size walls continuously.	Medium-low precision in printing elements with high geometry complexity. The transportation and assembly processes could be more complex and take more time than the Robotic and Telescopic Arm.

1.4. 3D printing process in construction

The building process using 3D printing technology can be divided into three main stages: (1) Computer-Aided Design; (2) Computer-Aided Manufacture; and (3) installation of utilities and finishes. Even though the first two stages are entirely connected to CAD and CAM, it is necessary to continue and finish the building process by conventional construction activities in the final phase. The stages are as follows [9]:

1. Computer Aided Design – CAD (3D model of what will be built)
   - 1.1. Architectural Design
   - 1.2. Structural Design
   - 1.3. MEP Design
2. Computer Aided Manufacture – CAM
   - 2.1. Model Analysis: Analysis of the project's constructability using 3D printer technology
   - 2.2. Exporting: generation of a file in a specific format, e.g., stereolithography file (STL) or additive manufacturing file (AMF), with all the geometric information to build the project
   - 2.3. Importing and slicing: conversion of the digital model into a list of commands (G-code) that the 3D printer can understand and carry out
   - 2.4. Printing: transportation and preparation of the machine, transportation of building material, beginning of the printing process, vertical and horizontal reinforcement installation, and lintel installation
   - 2.5. Post-processing: after the material is printed, a curing period is necessary to increase the strength of the walls
3. Utilities and Finishes: the final stage employs traditional construction methods, including the installation of roofs, doors, windows, utilities, and surface finishing of exterior and interior walls.

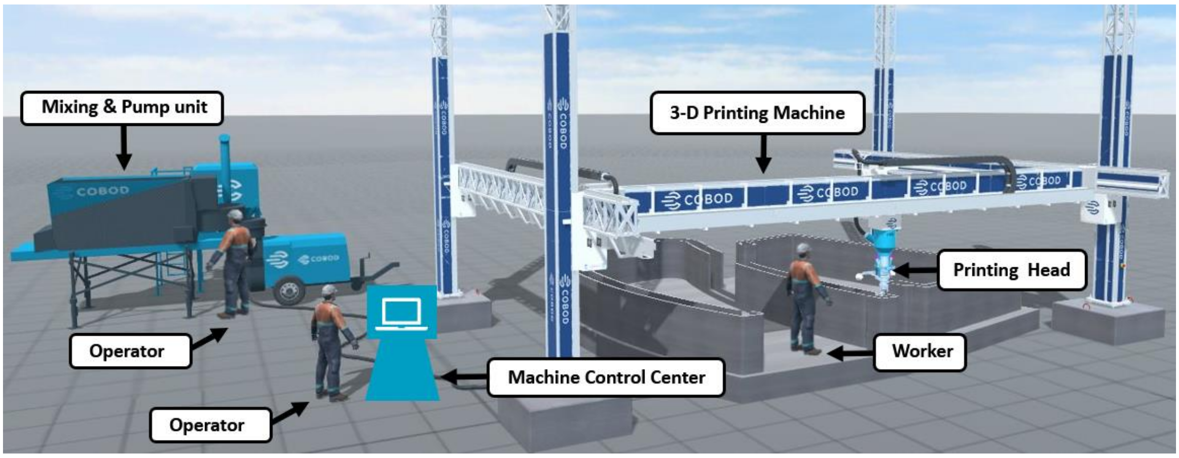

Fig. 4. Components of 3D printing machine, Gantry System [7]

1.5. Materials for 3D printing in construction

New construction methods require materials with up-to-date characteristics and specifications. For 3D printing of a house elements, new materials have been introduced to respond to the technology's requirements. According to Kashani and Nago [10], materials suitable for 3D printing need to have three main properties: (1) high workability for extrusion, (2) short curing time, and (3) strengthened resistance to support successive layers of material. As a result, a mixed material that can fulfill these conditions is required for a successful 3D printed construction project.

Concrete is one of the most used materials in the construction industry. However, this material cannot be extruded due to its aggregates' size. Thus, mortar has been used successfully with 3D printing technology [11]. Additionally, researchers also experimented with earth-based materials such as soil and thermoplastic polymer materials that appeared to be effective. The use of these three materials is explained below.

Mortar is a workable material based on a mixture of sand, water, and cement [12]. Typically, mortar is used to join building elements such as bricks and blocks. Recently, that material has been used as the main element in manufacturing walls using 3D printing. In 2022, ICON, an American company, built the House Zero project in Austin, Texas [13]. The walls were built using their own mortar called Lavacrete. It is a cementitious-based mix that offers high strength and can resist severe weather. Lavacrete has a compressive strength of 2,000 - 3,500 psi and can withstand extreme weather and significantly reduce the impact of natural disasters such as earthquakes while providing maximum efficiency. For example, ICON's homes in Nacajuca, Mexico, can endure severe conditions and have already resisted a 7.4 magnitude earthquake [14]. Furthermore, the ICON team [15] explains that Lavacrete reduces heat transfer by adding thermal mass to the home. In addition, thermal mass, increased insulation, and an airtight wall improves energy efficiency.

Soil is a natural body made up of solids (minerals and organic matter), liquids, and gases found on the Earth's surface [16]. This is one of the oldest construction materials used for building houses. In 2021, the Italian company WASP (World's Advanced Saving Project) built TECLA (Technology and Clay Project). This is a prototype of an eco-sustainable house printed using a mix of locally sourced subsoil, water, and binder. The project was a challenge in mixing one of the oldest building materials with the newest construction processing techniques.

Polymer is "a chemical substance consisting of large molecules made from smaller, simpler molecules" [17]. Polymeric materials are present in several construction elements, including walls, ceiling panels, and piping systems. Following the idea of manufacturing construction elements, the American company, Branch Technology, prefabricates panel systems using fibre-reinforced polymers and 3D printing. Its panels have an internal structure that decreases the weight and optimizes the use of materials.

1.6. Sustainable Buildings

As climate change mitigation efforts become widespread through regulations and social pressures, the AEC industry is focused on becoming more environmentally friendly. Sustainability as defined by the Environmental Protection Agency (EPA) is: "Everything that we need for our survival and well-being depends, either directly or indirectly, on our natural environment. To pursue sustainability is to create and maintain the conditions under which humans and nature can exist in productive harmony to support present and future generations" [18]. The goal of many modern designs is to create a sustainable structure to minimize the impact on the environment. An effect of this goal is reducing energy consumption, which in turn saves money in operation costs. The criteria for these modern designs have both public and private entities involved in pursuing the goals. On the public side, numerous states and cities have enacted building codes which push new construction to be more sustainable such as Boston and New York City. The various private organizations such as Passive House or Leadership in Energy and Environmental Design (LEED) set building certifications that modern building owners want. This can be seen through private building owners pursuing these certifications. Since the introduction of LEED in 2000, there has been over 110,000 projects that received different levels of LEED certification [19]. In addition to the private sector's acceptance of LEED, the public sector in many jurisdictions now require their own public buildings to be achieve LEED certification.

What makes a building sustainable is the combination of the materials used to construct it and the efficiency of the operation of that building. Just using sustainable materials or only ensuring a high-efficient building is one sided and does not provide a comprehensive solution. This is further broken down into the concept of embodied carbon. Embodied carbon is the total carbon dioxide (CO_2) associated with manufacturing of materials, transportation, and construction methods used during the whole lifecycle of a building. Once a building is built, operational carbon measures the energy consumed to operate the structure. This measures the heating and cooling loads, ventilation, lighting, power, lifts, automatic doors, and heating water. A true sustainable building should focus on both embodied and operational carbon.

1.7. Resilient Buildings

A part of creating a sustainable built environment is the longevity of the structures. The longer the lifespan, the more sustainable the building is, and this is where resiliency comes into play. Built environment resiliency is how well the structure can withstand the environment including the normal wear and tear of occupancy along with environmental forces such as storms and floods. As the world becomes more extreme in weather events, the need for resilient homes is paramount. A key area within the United States where resiliency should be the focus, in near future, are the Gulf Coast, Tornado Alley (Midwest), and the Rocky Mountain west which experience hurricanes, tornados, and devasting wildfires, respectively. These areas need housing and buildings that can be resilient to the natural forces they will unavoidably be exposed to. The consensus behind climate change is an increasing frequency of more powerful storms and larger swings between dry and wet seasons, all of these present a future that requires a departure from the current building methods to a more durable type of structure that can resist high winds, debris impact, flood, and fire. In any given year, homes are destroyed in America by tornadoes, hurricanes, wildfires, floods, and earthquakes highlighting that the current method of construction does not meet the current and future needs of a resilient structure, let alone the predicted intensified future events.

1.8. Affordable Housing

The need for affordable housing is a dire need in all locations across the world. Even within the United States, homelessness is an issue in all major cities. The cost of housing has been increasing at rates that far outpace wage increases. What makes housing affordable is if the cost of housing is less than 30% of the 0households' income [20]. The exact dollar figure ranges based on local demographics but the results of lack of affordable housing are well documented. A stable housing situation provides children and adults the stability to have better outcomes in their health, employment, and education [15]. Affordable housing does not only affect the lowest income earners. When using average income median (AMI), which is the average family income in a geographical location such as a metropolitan area, all ranges of income earners are affected. One the lowest end of income earners, there is only 32 affordable and available rental properties for every 100 renter households [21]. For households at the AMI, this number is 102 affordable and available homes per 100 renters, which is the only surplus of housing seen for all percentages of AMI at 100% AMI or lower [21]. Affordable housing is expanding into all levels of income and is becoming an increasing problem in areas that are experiencing rapid growth of population and limited housing growth.

2. 3D Printed Solutions

2.1. Sustainability with 3D printed homes

A key point to create more sustainable buildings is reducing the overall embodied carbon. 3D printed homes are currently made from a form of concrete which is a leading emitter of carbon dioxide (CO_2). This is related to the process of making concrete and its key ingredient Portland Cement [22]. There are currently numerous efforts to reduce the embodied carbon in concrete such as using alternative products in the mix such as fly ash, slag, crumbled recycled concrete, and other waste products [23]. This helps reduce the embodied carbon and takes pressure of landfills where this waste would normally end. The 3D printing materials allow for more flexibility in implementing recycled products, reducing the need for new products, and diverting less waste to landfills.

A large part of creating a sustainable construction industry is reducing the waste generated from the building process and reusing materials from demolitions to prevent the useful materials from going to waste and forcing new materials to be created to fill that void. 3D printing reduces the carbon footprint by limiting the number of materials required on site through the method of construction, or the elimination of major areas of traditional building. The reduction or elimination of wood framing, minimal interior finishing, and minimal labour provide savings on the emissions from numerous deliveries of multiple materials and the volume of workers traveling to the site. The average waste during a house construction is 2 tons of waste [24]. Prefabrication plays a huge part in reducing waste. Studies show that prefabrication can reduce waste on average by up to 50% [25]. From efficient designs that can print foundations and walls without forming or waste from cutting materials to size, printing and using the exact number of materials is a strength of printing homes. Many 3D printing companies use wooden trusses to complete the roof which come prefabricated. Prefabrication is used even more commonly as some 3D printed homes are 3D printed assemblies that are built in factories and then shipped to the site to be assembled into the final structure. This reduces all the waste as the 3D printed assemblies in the factory allow for precision material use with minimal waste.

2.2. Resiliency with 3D printed homes

The use of concrete to make structures that resist impacts from both natural and human forces is a customary practice. With the growing strength and frequency of extreme weather events, the current building methods are struggling to stay resilient. 3D printed homes are typically constructed from a cementitious material that in many models performs like concrete masonry units (CMUs). The building codes are not uniform, but buildings need to meet code standards and are considered an alternative means and method in the International Building Code and each project needs to show its conformance to the required aspects [26]. Regardless of building code status, the materials used in the printing process creates strong structures that can resist impacts from natural forces. The resiliency of a building plays a key role in the sustainability. The more resilient, the longer the life span, which in turn reduces the need for construction of new buildings to replace the current stock. This helps the structure be more sustainable as well.

The current life cycle analysis of 3D printed homes is still in its infancy, the longevity of the structures has yet to be seen but the hopes are high. As the current buildings begin to age, further research needs to be conducted to monitor the durability of these structures. Many companies have a few 3D homes printed as models as a proof of concept to sell their investment opportunity to investors and some have large scale communities planned and scheduled for ground-breaking in 2022. This year, 2022, has numerous projects starting up that have 3D printed homes at the centre of the project. A community is planned in Texas by ICON and the current projects being conducted by SQ4D in New York that sell at 40% cost of comparable traditionally built homes [27], [28]. This provides limited data for review and full assessment of actual performance and requires a review of the materials used. This is true regarding all structures, the type of materials used play an important role in the performance of the building. Cement can resist fire, but if the roof and windows use wood or other flammable materials, the building would not be resilient against fires. For 3D printed homes to be resilient, the products used alongside the cement need to be carefully examined and reviewed to ensure the entire system is resilient to the threats of specific location that they will be built. The current status of 3D printed houses looks promising and future research is needed to confirm the theory that this technology provides resilient houses in the future.

2.3 Affordability with 3D printed homes

Labour and time are large factors in the cost of construction. Current homes depending on their size and design, require multiple different contractors to mobilize and complete their work in sequence. In 2021, the United States average timeframe for a house to be built was 7 months [29] compared to the days that it takes for the exterior shell of the building using 3D printing [27]. The total time for finishing the interior of the building to an occupiable space can take 4 – 6 weeks, but in some cases just days. Time is money, the more man hours expended on a build, the higher the cost. The cost savings range greatly in the cost of the printed homes, but most companies state between a 30% to 40% reduction in cost [27]. Habitat for Humanity, which uses voluntary labour to construct their homes even saw a 15% reduction in cost to their average cost for a home [30]. This could be due to the reduction of waste which reduces the cost of require materials. The fast-paced 3D printing allows minimizing the amount of labour costs and maximizing production rate of buildings. This should in turn increase supply, decreasing demand, and lower the price based on economics. In addition to this, the trend of the housing market is such that the cost of building a new home, sets a benchmark for the existing housing stock. This premise works out to be that the higher a new construction house costs to produce, the existing housing stock value increases as the sole competitor which is new construction costs more. The past few years have seen unforeseeable disturbances to all markets and the housing market was no exception. With this acknowledged, prices of traditionally built homes were higher before the pandemic than the 3D printed homes of that period. Acknowledging the unprecedented past few years, the housing prices before the pandemic were lower but still above the cost of 3D printed homes.

3. Cost Comparison

Affordability is based on the cost of the building. Currently, housing prices can be blamed on a variety of reasons ranging from zoning regulations, interest rates, shortage of housing, and growing populations especially in urban areas. While 3D printed homes cannot address some of these issues that are causing shortage of affordability housing, 3D printed homes can be constructed quickly and cost effectively. When comparing the sale prices of 3D printed homes, the sale price in some locations can be half of the average of selling price of comparable traditionally built homes. For example, SQ4D has sold a small number of homes for around 40% of comparable homes [27]. Other printing companies also advertise the lower cost of their properties. One of the larger costs in all construction projects is the cost of labour. Labour cost can range from 20 to 40% of the total cost of a project. 3D printing reduces the amount of manhours spent on the project, which will reduce the overall cost of a project. In addition to reducing the number of hours spent working on the project, the turnaround time is faster. This means more projects can be completed in the same period of time. The speed to construct can help overcome the current shortage of housing in rapidly developing or expanding cities. Table 2 highlights certain facts about the costs of 3D printed homes in comparison with traditionally built homes.

Table 2. Studies on the cost comparison of traditional and 3D printed homes

Reference	Highlights
[31]	Homes can be printed within 24 hours and just for $4,000. These are post-disaster shelters, but this shows the versatility and affordability of 3D printed homes can bring.
[32]	Depending on the printing company cost savings range from 15% to 50%.
[33]	3D printing can reduce costs by 20-40%.
[34]	With the right printing material design, most of the printing compound can be locally sourced with little shipping requirement from a central stocking location.
[35]	Countries that depend heavily on migrant labour can save up to 50-80% on labour costs from 3D printing. A reduction of waste was reported between 30-60%.
[36]	The savings from 3D printing can be up to 35% in overall costs and a reduction of 91% in total man-hours.

4. Limitations

5.1. 4.1. Current limitations of 3D printing in construction

The application of 3D printing to the construction sector is in its initial stage since its practice only began around a decade ago. Although the AEC industry can learn from the 3D implementation in other industries, this process could be more complex in the building sector due to the scale of the projects, the diversity of materials, the variability of the environment, and the building codes, among other factors [1]. Therefore, there are multiple challenges that this technology needs to solve, such as construction codes, workforce reduction, and maintenance processes.

As it is often the case with implementing the latest technologies, the challenge is that laws and regulations sometimes cannot track innovation fast enough. As Kroes [37] explains, when 3D printing moved from the conceptual stage to the construction site, a gap emerged between the available technology and the construction industry standards such as building codes, permits, inspection authorities, and contractual provisions for new buildings. However, this code does not have any provisions or guidance related to 3D printing. Therefore, the International Code Council (ICC) Assessment Service developed an acceptance criteria document for three-dimensional concrete walls (AC509) under Section 104.11 of the IBC. The recently released AC509 focuses on wall construction using 3D printing, evaluating the material's structural strength, fire resistance, and durability. AC509 also details the specific product quality and sampling standards required to achieve code compliance [38].

Although one of the advantages offered by 3D printing technology is automation and cost reduction, it is crucial to understand the side impacts it can also generate. A widespread problem with the automation of manufacturing activities is the reduction of the workforce. Since construction is an essential source of employment in many countries, eliminating jobs may affect laborers significantly. For example, if activities such as masonry were totally automated, workers of this trade would have to move to other sectors or learn different skills. The construction industry will have to face this challenge since the workforce is an essential part of its growth.

The maintenance of buildings, known as all the activities that focus on preserving and restoring the functionality of a building, is of vital importance. Currently, a significant advantage is that mechanical, electrical, and plumbing systems can be integrated into the 3D printing process. However, questions arise regarding the maintenance and repair of these systems and the manufactured walls using this type of technology. For example, if there are leaks, humidity, or a need for pipe inspection, perforations on the walls may be necessary. Since 3D printed walls mimic the CMU building method, repatching perforations or cracks are similar to repairing a CMU wall. The process consists of (1) preparing the surface and cleaning the hole in the wall, (2) applying a bonding agent, (3) repatching/repairing/filling the hole in the wall using mortar or patching cement, and (4) finishing and painting the repair to match the surrounding. 3D printed walls can be cut and drilled as standard CMU or concrete walls. 3D printing technology merely shifts the way walls are constructed from manually to robotically. Therefore, processes such as repairs or maintenance are not affected [6].

5. Conclusion

As 3D printing becomes a more integral part of the construction industry, the above problems will be alleviated. Thus, establishing relationship between the different parties such as companies, government, and academia is necessary. In this way, new building processes and tools will be developed to eliminate the current limitations and provide more advantages for constructing sustainable, resilient, and affordable housing. Although 3D printing technology for the construction industry is an outstanding tool, it will not solely transform the AEC industry on its own. That technology must continue to evolve to meet current standards and construction practices. Training and developing new skills in construction professionals will be necessary to generate a new workforce that takes advantage of this technology.

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