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REVIEW ARTICLE

A critical review of 3D printing in construction: benefits, challenges, and risks

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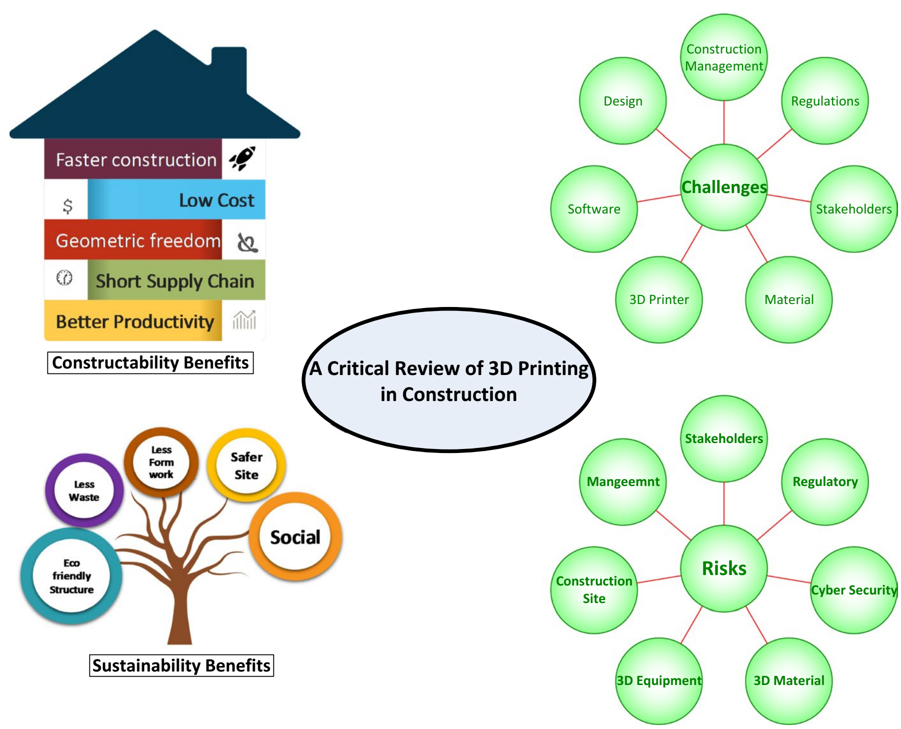
Abstract

This paper provides a critical review of the related literature on 3D printing in construction. The paper discusses and evaluates the different 3D printing techniques in construction. The paper also discusses and categorizes the benefits, challenges, and risks of 3D printing in construction. The use of 3D printing technology offers several advantages over traditional methods. However, it comes with its own additional challenges and risks. The main benefits of 3D printing in construction include constructability and sustainability benefits. The challenges are categorized into seven groups. The main challenges, found through the literature, are material related. The most cited challenges are material printability, buildability, and open time. Additionally, scalability, structural integrity, and lack of codes and regulations are frequently cited as major challenges. The additional risks are categorized into seven groups: 3D printing material, 3D printing equipment, construction site, and environment, management, stakeholders, regulatory and economic, and cybersecurity risks. The paper fills a gap in the literature as it addresses a new aspect of 3D printing, which is risk. The paper also provides some insights, recommendations, and future research ideas.

Graphic abstract



Extended author information available on the last page of the article

Keywords 3D printing in construction · Smart construction · Risks · Risk management

1 Introduction

The construction industry is one of the largest industries in the world. With annual revenues of nearly 10 trillion USD, or about 6% of global GDP, the engineering and construction industry is a cornerstone of the world's economy [1]. There have been many advances in the construction industry in the past decades [2]. Construction companies are consistently looking for methods to increase productivity and at the same time reduce cost [3]. Labor productivity in the manufacturing industry has been increasing. However, studies have shown that over the years, labor productivity in the construction industry has been declining [4]. Lack of implementation of new technology is one cause of this decline [5]. The fourth industrial revolution, known as Industry 4.0, promotes digitization of the most complex industrial tasks. This trend was mainly applied to the manufacturing industry and its applications in the construction industry which is still at its early stages [4]. Additive manufacturing (AM), or more commonly 3D printing, is one of the newest forms of technology that has been introduced in the construction industry, which could be considered as one of the main drivers toward the digitalization of the construction industry. Automotive industry and manufacturing industry benefited from the variety of technologies brought by Industry 4.0, which resulted in improvements in the quality of the products and an overall increase in the performance [6, 7]. Despite these benefits, Industry 4.0 was not adopted in the construction industry with the same pace as in the manufacturing industry [7]. Dallasega et al. [8] attempted to explain how the Industry 4.0 concepts are changing the construction industry and its connected supply chains. Others [3] studied the changes Industry 4.0 is bringing to the managerial side of the construction industry. Alaloul et al. [9] investigated the digitization of the construction industry based on the technologies brought by Industry 4.0. Additive Manufacturing (AM), or more commonly 3D printing, is one of the newest forms of technology that has been introduced in the construction industry.

The first printer was developed by Charles Hull in 1984, and since then different applications of this technology have been applied to several industries [2, 3, 10]. 3D printing can be used to print anything that is sketched in 3D as it requires a CAD file, or a 3D digital model to execute the project. Some examples of this type of software include SolidWorks, Inventor, Google SketchUp, and in the construction industry BIM software such as Autodesk Revit [11–13]. 3D printing has been beneficial to several industries including the aerospace, automotive, and healthcare industries [14]. 3D printing is used in medicine [11, 12], the automotive industry [15], and the food industry [12]. Recently, there has been a growing interest in construction automation and the applications of 3D printing in construction. Several number of drivers are pushing construction toward automation: lowering labor for safety reasons; reducing construction time onsite; reducing production costs; and/or increasing architectural freedom [16]. Additionally, 3D printing helps address sustainability issues. The construction industry has been recognized as one industry that consumes a considerable amount of resources and poses significant environmental stresses [17].

Implementing 3D printing in construction projects creates additional risks. Risk is an uncertain event that may have a negative or positive effect on at least one of the project objectives [18]. Construction projects are naturally risky endeavors as they involve the use of different materials and several project stakeholders with different objectives. Additionally, construction is performed outdoors, which makes it subject to natural risks. Risks are a major threat to project success [19]. Failure to adequately deal with risks causes cost and time overruns in construction projects [20]. Risks in construction projects are classified as internal or external risks [21]. Internal risks are at the project level (microlevel), while external risks are at the macrolevel. External risks include political, environmental, and socioeconomic risks. Internal risks include technical, design, material, contractual, and liability risks.

With the introduction of any new technology in any industry, uncertainty and risk arise. A research was performed on a new technology in nuclear power plants, and 29 risks were found. Some of the risks found were lack of sufficient knowledge of the introduced technology, practical constraints like availability of equipment supply, and effects on the interfacing systems according to the introduction of the new technology [22]. Additionally, a survey was conducted to see the advantages and disadvantages of using entry-level 3D printers in small businesses. The main disadvantage was that the machine was unreliable and required a great deal of maintenance [23]. Although there are several advantages of this emerging technology, it comes with its own additional risks. Malone [24] reported that the first 3D-printed building was completed in Copenhagen a few weeks behind schedule. The delay was attributed to faulty material deliveries and equipment failures related to material handling [24].

Few review papers addressed 3D printing in construction. Bock [4] reviewed recent trends in construction automation and showed that over time, the ability of robot systems has grown. Camacho et al. [14] reviewed several applications of 3D printing in construction with a focus on mechanical systems and materials and offered future directions related to onsite implementation. Paul et al. [25] offered a review of 3D concrete printing with a focus on the printing systems and materials properties including the use of reinforcement bars or fibers. Additionally, Ghaffar et al. [26] reviewed the systems and materials for 3D printing and discussed the sustainability-related benefits. Lim et al. [16] reviewed recent developments in 3D printing with a focus on concrete as a printing material. Uppalla and Tadikamalla [27] reviewed 3D printing in construction with a focus on sustainability aspects. As for the challenges, Labonnote et al. [28] reviewed the challenges and opportunities of 3D printing in construction and classified them into material science, engineering, building design, and market analysis. Bos et al. [29] identified the main challenges and potentials of 3D concrete printing. Wu et al. [17] reviewed 3D printing applications with a focus on challenges to its implementation on large-scale projects. Tay et al. [30] reviewed the research on 3D printing from 1997 to 2016. They showed that the frequency of publication was slow until 2009, when a clear gain of interest in 3D printing in construction triggered an increase in the rate of publications in this area of research. Shakor et al. [31] reviewed the technology in 3D printing of cementitious materials. In this paper, the authors focused on aspects of concrete mix design and they presented some new mixes, which were tested to determine their characteristics. Hamidi et al. [32] reviewed the literature on cementitious composites. The authors investigated the state of the art related to the different techniques to reinforce cementitious composites during the printing process and they highlighted the important role of cement-based materials in the future of 3D printing.

These review papers addressed important and recent trends in 3D printing in construction. Each has offered a review over specific areas such as 3D printing systems, materials, and sustainability. However, there is a lack of a broader coverage of all challenges related to 3D printing such as material, printer, software and computational, architectural and design, construction management, regulatory and stakeholder- challenges. Additionally, there is no coverage of the potential risks associated with implementing this technology in construction projects. This paper offers a comprehensive review of related literature on 3D printing in construction. The objectives of this paper are threefold. The paper discusses and evaluates the different systems of 3D printing in construction. Secondly, the benefits and challenges of 3D printing in construction are discussed and categorized. Thirdly, the paper identifies the main risks associated with the new technology. The paper concludes with specific recommendations to address the risks and challenges and it offers future research ideas.

To achieve these objectives, a comprehensive review methodology was followed. The search targeted databases such as Science Direct and Web of Science, Elsevier, Taylor and Francis, Emerald and American Society of Civil Engineering (ASCE). The search terms included 3D printing, Additive Manufacturing (AM), 3D printing in construction, construction automation, and construction risks.

2 Additive manufacturing

2.1 3D printing

3D printing is defined as the process of making an object from a three-dimensional model by adding thin layers of material on top of each other [28]. Figure 1 presents a schematic that shows the difference between classical manufacturing (subtractive) and 3D printing or Additive Manufacturing (AM). AM is defined by the American Society for Testing and Materials (ASTM) and the International Organization for Standardization (ISO) as

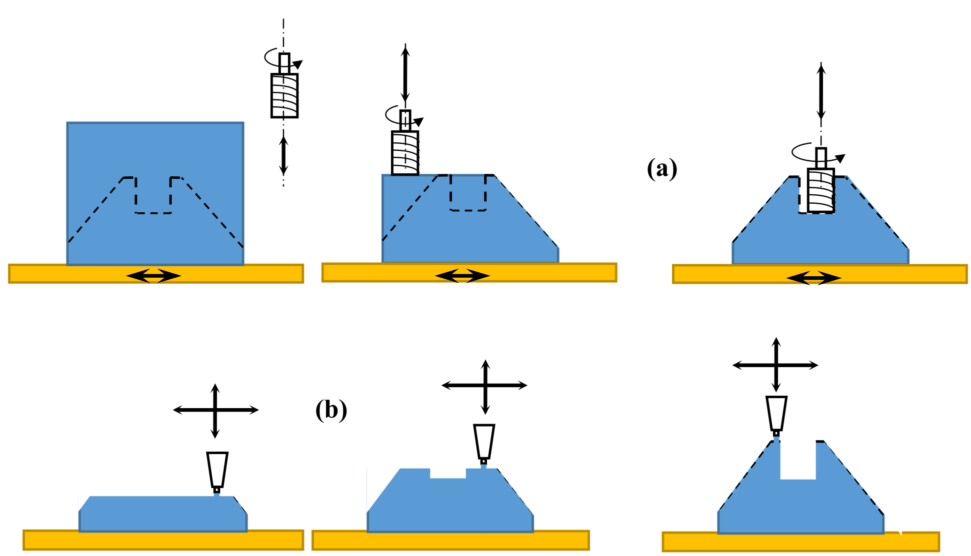


Fig. 1 Comparison between **a** classical subtractive manufacturing and **b** AM

'the process of joining materials to make objects from 3D model data, usually layer upon layer' [33].

The main advantage of AM is its ability to produce parts from a CAD model, which saves time and cost mainly for prototypes. Gibson et al. [34] classified AM systems in Photopolymer-Based Systems, Powder-Based Systems, Molten Material Systems, and Solid Sheets Systems.

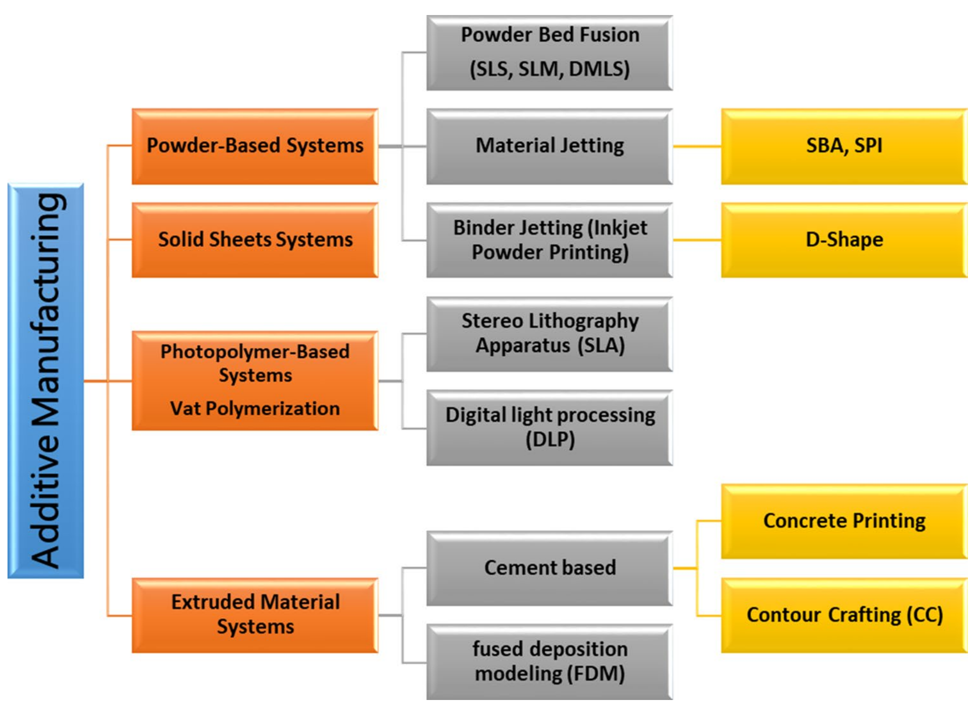
Different techniques are used for AM. Figure 2 lists the most common ones used for each process. It is worth mentioning that this classification is based solely on the type of material used in each process. The two techniques related to Additive Manufacturing for Construction (AMC) are found in powder-based systems and extruded material systems. In the first type, several techniques can be identified, i.e., selective binder (cement) activation (SBA), selective paste intrusion (SPI), and binder jetting, using a technique called D-shape [35]. For the extruded material system, the material used is a concrete mix, which is fed in through the nozzle using a pump. More details on this technique will be presented later in this paper.

The focus of this paper is the application of 3D printing in construction, where large-scale 3D constructions are needed. Experimental application using 3D printing in the construction industry started in the early 1990s [14]. One of the applications of 3D printing in construction is the reproduction of historical building ornamental components [36]. Another application is the spall damage repair on concrete roads [37]. Furthermore, NASA is interested in the potential of 3D construction in space [38].

Figure 2 shows the main types of additive manufacturing. The powder-based systems use a powder with a binder to selectively deposit the binder/powder to build the structure as the mix powder-binder hardens. A second way to use the powder is to melt it layer by layer using a laser source. The process of solid sheets builds the part layer by layer using precut sheets of metal, which are bound together using different techniques. The Vat polymerization is based on solidifying a layer of a liquid photopolymer resin using ultraviolet light to cure photosensitive polymers type beam. A bed supporting the layers is lowered after each layer is solidified. Stereolithogrphy process was patented by Hull in 1987. The most common type of 3D printing is based on material extrusion. The material in this case is a plastic wire, heated and extruded then selectively deposited where it fuses to the existing structure and hardens as it cools. In construction, the cement is extruded to selectively deposit it.

There are typically five types of 3D printing that are used in construction: contour crafting (CC), concrete printing (CP), selective binder (cement) activation (SBA), selective paste intrusion (SPI), and D-Shape (Fig. 2) [16, 35, 39–41]. The first two types can be classified as "Extruded Material Systems" and the last three as "Powder-Based Systems" (Fig. 2). Indeed, contour crafting and concrete printing are similar and they are both based on injecting a mix (usually mortar) through a nozzle to generate the printed part. In this case, the process is similar to the FDM methods except that the material is already fluid and no heating is required. However, a pump is required to feed the mix through the nozzle. For the SBA technique, a dry mixture of very fine aggregate

Fig. 2 Additive manufacturing techniques



and binder (cement), which is locally activated by selectively spraying the binder onto the packed particles thus forming a cement paste matrix around the aggregate particles. Selective paste intrusion process consists of selectively injecting the binder on the particles, where the binder is a paste of cement, water, and admixtures. The cement paste should be liquid enough to fill the spaces between the particles. The D-shape technique uses a printer with an array of inline nozzles to print large objects. The printer builds the object layer by layer using sand, where each layer is selectively sprayed by a binder. The unbounded sand remains around the printed layer, which is solely used to temporarily support the construction. The binder is typically a resin which reacts with a hardener component in the particle bed [39–41].

Initial concepts for using 3D printing in construction came from Pegna in the early 1990s [16]. Khoshnevis [42] from the University of Southern California later on developed contour crafting [14, 43, 44]. Contour crafting uses a gantry system to extrude concrete. The system has trowels attached to the nozzle which aide in smoothing out the surface of the concrete as it is being extruded [45]. This type was the first additive manufacturing method for onsite construction of custom structures [13]. The advantages of this technology include better surface quality, higher fabrication speed, and broader choice of materials [13]. Limitations of this technology include: only vertical extrusions are possible, complex to implement for production, the possibility of weakened interfacial zones between the layers due to hydrostatic pressure and weak mechanical properties of the extruded cement [39]. Contour crafting caught the interest of NASA for its promising approach for construction on the Moon and Mars [13] and it won the grand prize by the agency in 2014 [38]. The materials used with contour crafting are concrete, polymer, and ceramic [46]. The materials will be discussed more in detail in Sect. 2.4.

D-shape is another type of 3D printing, which was developed by Enrico Dini in 2005 [35]. D-shape process uses powder as the material and is hardened using a binder, which is usually a resin that reacts with powder bed [16, 40, 41]. First, the chosen powder material is layered to the desired thickness and then the binder is deposited to the areas to be solidified. Later on, the 3D-printed material is taken out of the powder or sand bed [16, 26, 45].

Concrete printing usually uses high-performance concrete as the material. This process allows more geometrical control [16, 45]. Concrete printing uses SLA printers, which was the first 3D printer that was developed by Charles Hull, mentioned earlier. “Selective solidification (SLA) makes a solid object from a vat of liquid by selectively applying energy to solidify the liquid a layer at a time” [2] (Fig. 3).

The three types of AM mentioned earlier (contour crafting, D-shape, and concrete printing), all are methods in which the material is extruded out of a nozzle. Another technology that uses selective deposition is also defined as 3D printing. Selective deposition techniques only place material where it is needed [2].

2.2 Robotic system

In recent years, there has been significant improvement in developing large-scale 3D printers to have a larger workspace, capable of printing industrial-scale 3D buildings [17]. The two most common methods of delivery in 3D-printed construction are the gantry system (Fig. 4) and articulated robot systems (Fig. 5). Gantry system follows the Cartesian coordinate system where the nozzle of the printer moves in three axes (X, Y, Z) [28]. Limitations of the technology include transportation, installation, and size. Figure 4 shows a gantry robot serving a print area of $9 \times 4.5 \times 2.8$ m. Besides the three Cartesian translations, the printer head has a rotation around the z-axis. This extra degree of freedom is used to rotate the nozzle when the head changes direction from a rectilinear motion. To avoid twisting of the filament, the nozzle has to remain tangent to the tool path, which requires a large curvature when the nozzle changes direction. This limitation makes obtaining sharp corners almost impossible when 3D printing concrete (Fig. 4b). Besides the limitation due to the material behavior, there are limitations due to the robotic system itself. Indeed, sharp corners require a discontinuity in the velocity of the nozzle, which generates infinite acceleration. However, most of the robot systems have a limitation on their maximum acceleration required by the type of actuators used. During the printing operation, the robot can approach a singular configuration, where joint oscillations can become excessively high, which deteriorates the quality of the printed layer. Apis Cor [47] proposed an algorithm, based on the pseudo-inverse of the Jacobean matrix to ensure the generation of smooth trajectories when the robot approaches singular configurations. Another method of delivery is the articulated robot system, which consists of a robotic arm. A robotic arm requires less space than a gantry system and can be mounted to a transportable platform providing ease in onsite structures [14] (Figs. 5, 6). However, the workspace is usually limited compared to gantry robots. Indeed, the maximum reach of the robot is limited by the high moments generated at the base when the robot reaches its maximum extension (Fig. 5). This robot is called a cylindrical robot, where the first joint is a vertical translation, the second joint is a revolute and the third is a telescopic translational one. Using this structure, generating sharp corners is also difficult and circular paths are the easiest in this case, which could explain the circular shapes in Fig. 5. Only three degrees of freedom (DOFs) are used in this case. However, for more complex geometry, more DOFs are required. These DOFs are used to change the orientation of the nozzle required when executing complex 2D motion,

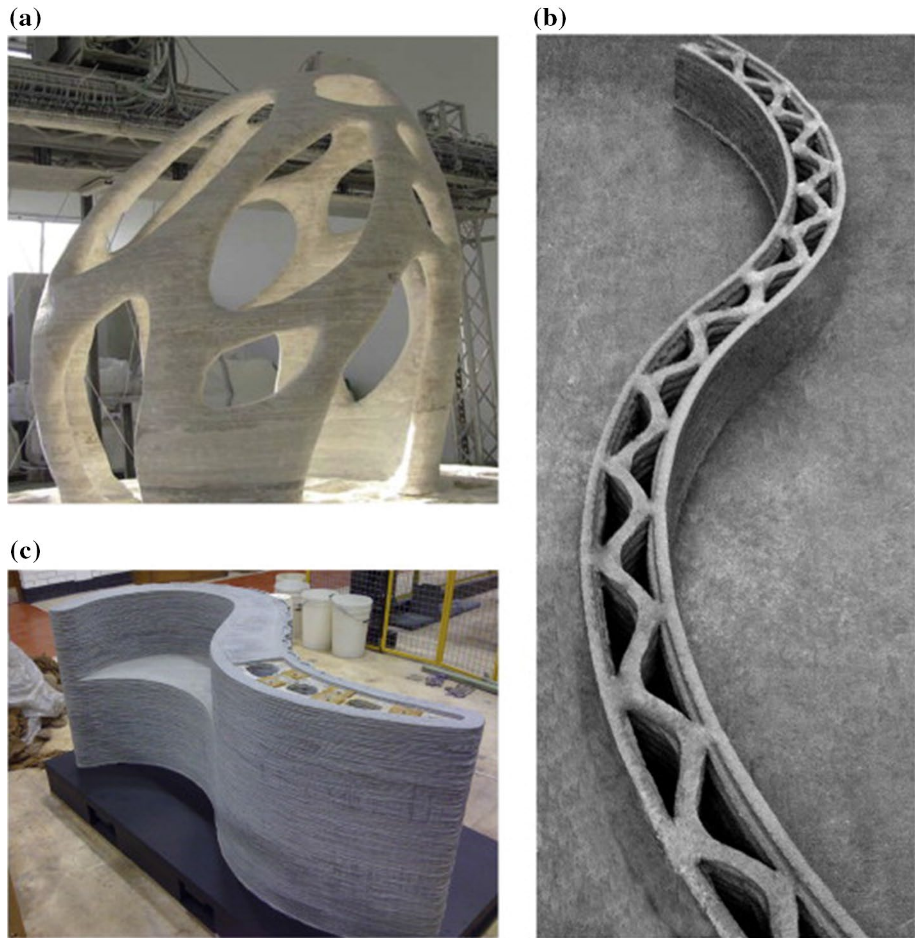


Fig. 3 D-shape (**a**), Contour crafting (**b**), and concrete printing (**c**) [16]

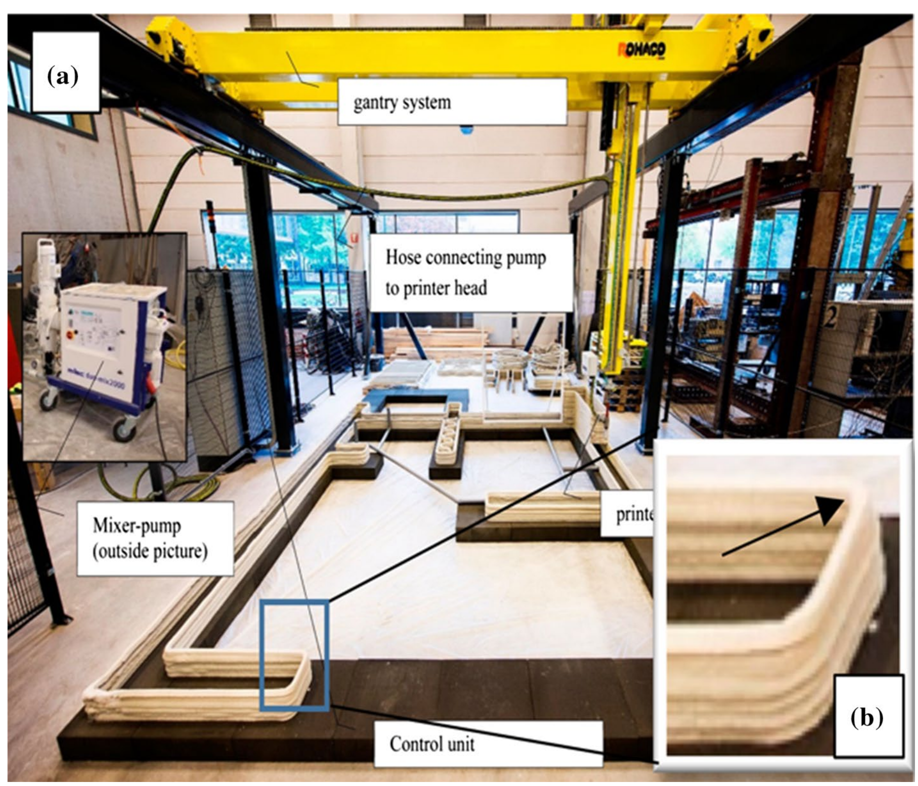


Fig. 4 **a** Gantry system in construction, **b** rounded corner of the contour [29]

Fig. 5 Articulated robot system [3]

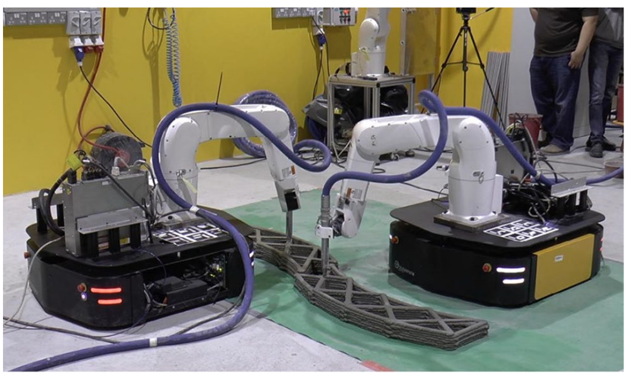


Fig. 6 Concurrent printing of a large, single-piece, concrete structure by two mobile robot printers [48]

e.g., sharp corners. Since the printing is made layer by layer, there is no need for more than four DOF, where the fourth DOF is used to rotate the printing head around the vertical axis.

Zhang et al. [48] suggested using a team of mobile robots to cooperate in printing large single pieces (Fig. 6).

To increase the size of the printed part, Barnett and Gosselin [49] propose to use a cable robot. This type of robots has the advantage of being less expensive, lighter, and easier to transport and to configure [49]. Figure 7 shows the structure used to print a 2.16 m high statue using foam. The fully constrained cable robot has the same limitations as the previously mentioned robots. However, one more limitation is encountered in this type of robots, which is cable interference causing a relatively limited workspace [49]. To reduce this effect and increase the size of the workspace the authors selected a gravity compensated cable robot, where the gravity maintains the tensions in the cables, at all times.

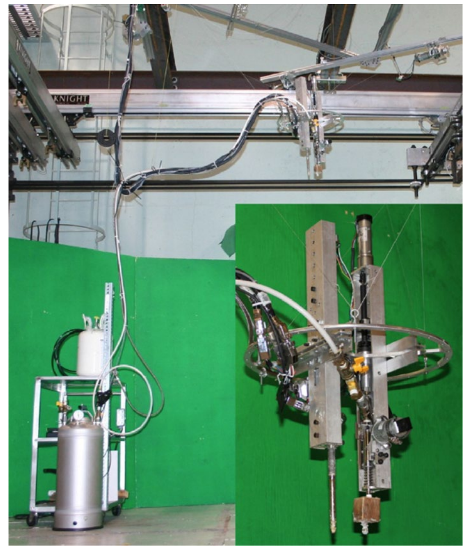


Fig. 7 The cable-suspended 3D foam printer [49]

This solution, called cable-suspended robots, comes at the expense of a lower accuracy compared to fully constrained cable robots [49]. The authors of [45] mentioned that sharp edges and narrow features are reproduced poorly. This error was attributed to the path generation algorithm, used to drive the robot. The cable-suspended robot has six cables and 6 DOFs, which is another advantage, as the fully constrained robot would require at least seven cables to achieve the same number of DOFs.

In conclusion, the two most used structures are the robot arm and the gantry system. The main difference between these two structures is their reachable workspace. Indeed, for robot arms, usually the reach does not exceed 3 m, which limits the size of the printable objects. Printing a full house, for example, using a fixed robot arm-based 3D printer, would not be possible due to this limitation. In this case, two solutions are proposed: The first one consists in printing sections of the building, which requires an assembly of these sections to obtain the final building. The second solution requires moving the robot arm around the construction to build the different parts of the building. In either case, this solution puts some limitations on the shape and size of the printed building. A printer based on a robot arm with 6 DOFs, however, has the advantage of being able to generate complex shapes as the nozzle, attached to the end-effector of the robot arm, can have all possible six motions in space (3 translations and 3 rotations). This reach, however, can be extended when using gantry type 3D printers. With this type of 3D printers, a full house can be built continuously, without the need to move the printer. Some companies [50] claim that using a gantry robot, a full two-story building of $12 \times 27 \times 9$ m can be printed, without the need to move the printer.

Fig. 8 Limestone and cement mixture with **a** high, **b** moderate, and **c** high workability level. As seen from the figure, this mixture is not considered printable [58]

Fig. 9 Printed house in Dubai [14]

3D-printed buildings can be a result of either onsite or offsite fabrication. Onsite 3D printing requires the transportation of the 3D printer, which can be difficult, and costly [3]. Offsite production is also known as pre-fabrication. In pre-fabrication, the parts are 3D-printed in a factory and then transported and assembled onsite. This was the case for the 3D-printed office in Dubai. The parts were printed in China and then shipped and assembled in Dubai (Fig. 9). Kothman and Faber [51] interviewed construction professionals on 3D printing in construction. Results showed that contractors were interested in onsite printing since they stated that offsite or pre-fabricated materials would always get damaged during transportation.

2.3 Material

The materials used in 3D printing should have certain specifications to be compatible with the technology. Research shows that the most common materials used in 3D printing are: cementitious materials, polymer materials, and metallic materials [14, 52]. Fused deposition modeling (FDM) or fused filament fabrication (FFF) focus on printing objects through melting of polymer [53]. Polymer materials are usually used for aesthetic purposes because of its lack of structural properties. This material will provide a low-risk option for implementing additive manufacturing technology in construction [14]. The most popular polymer base printing materials are ABS (Acrylonitrile Butadiene Styrene) and PLA (Polylactic Acid). They both are thermoplastic polymers, which means that they melt at high temperatures and go back to a solid state after cooling down [53]. PLA is considered to be more sustainable than ABS since it is biodegradable [10]. Metallic properties are also popular as a construction material; however, 3D-printed structures that consist of only metallic materials are quite heavy. Cementitious materials are the most used material in the technologies mentioned earlier, such as contour crafting and concrete printing. The concrete used in 3D printing should be a high-performance concrete. Le et al. [54] stated that a high-performance concrete has been developed that can build architectural and structural components without formworks.

The World's Advanced Saving Project (WASP) has created a 3D-printed house using earth materials. The materials used raw soil, straw, rice husk, and lime. The total cost of the materials used in the house amounted to 900 euros [53].

Quality and specifications play a major role in determining the effectiveness of concrete. There are four properties to ensure a successful 3D-printed structure:

- Pumpability, which is defined as the ease in which the material is pumped through the 3D printers pump;
- Printability or extrudability [55], which is the ease in which the material is pumped out of the nozzle of the printer;
- Buildability, which is the resistance to deformation of the deposited material under load, and
- Open time, which is the period where the pumpability, printability, and buildability are at an acceptable range [14, 16].

On top of these properties, other factors affect the successful printing of concrete. The printing speed affects the properties of the printed concrete and would determine whether there are weak joints between the layers. Similarly, the printing direction would affect the overall concrete properties [56]. As for the concrete mixes that would be compatible with 3D printing, Ghaffar et al. [26] state that printable materials are usually a mix of bulk materials, such as soil or crushed stone, mixed with Portland cement or fly ash, and workability additives. Additionally, Lim et al [16] state that a high-performance cement-based mortar has been developed. The composition of the mortar consists of sand, reactive cementitious compounds, and water. A study performed on high-performance printing concrete showed that the optimization mix consisted of cement, fly ash, and silica fume [57]. Another study performed regarding the concrete mixes used for 3D printing concluded that the types of aggregates that were able to be printed successfully included an adequate number of river sand and combination of river sand and limestone-based concrete mixtures [58]. However, it was determined that most of limestone-based mixtures were not printable (Fig. 8). Moreover, the mix with the highest strength levels was obtained for the river sand and limestone mixture [58].

Another aspect of the material to take into consideration is the reinforcements. This is an important factor to ensure that the structure does not collapse. Reinforcement remains one of the challenges of 3D printing in construction. One method of reinforcement of 3D-printed structures is placing the reinforcing steel bars manually between the layers before or during printing [25]. However, this method is challenging since the steel rebar creates an obstacle for the movement of the printer head. As a solution, a hollow structure can be printed and the rebars can be installed afterward with infilled concrete to connect the steel reinforcement with the printed structure [59]. Reinforcing 3D-printed structures with steel, however, alleviates the automated luxury introduced by the technology, since a considerable amount of labor is needed [29]. The steel reinforcements also increase construction time and cost [60]. Another method of reinforcing that is more suited for 3D printing is by using fiber-reinforced concrete, instead. This method would fully automate the process and offers greater geometrical accuracy, reduced manufacturing time as well as a decrease in labor cost [25]. An ultra-high-performance fiber-reinforced concrete, which is reinforced with steel fibers, has been developed. A study conducted using this type of concrete has been found to have favorable characteristics and therefore satisfies the requirements of most structural applications [61]. This type of concrete has been reinforced with steel; however, other fibers, such as glass or carbon fibers, can also be used for reinforcement [25].

Ducoulombier et al. [62] studied the interfacial properties between matrix and fibers in cementitious materials used in 3D printing. In their work, the authors focused on the fiber/matrix interface, which is the main factor governing the mechanical behavior of the reinforced material. Bos et al. [63] investigated the ductility of 3D-printed concrete reinforced with short straight steel fibers. They showed that the fibers improve the flexural strength of printed concrete bringing it to a value similar to the cast concrete. Feng et al. [64] studied the behavior of 3D-printed elements reinforced via a hand-lay-up procedure using glass fiber-reinforced polymers (GFRPs) reinforcement. The author showed that these reinforcements can improve the load capacity and ductility of the 3D-printed elements. Lowke et al. [41] investigated different techniques for particle-bed 3D printing on concrete. The authors presented a classification, which led to the selection of three techniques, i.e., selective binder activation, selective paste intrusion and binder jetting, as the most relevant to this type of 3D printing. Ingaglio et al. [39] tested a new technique using binder jet-printed CSA cement with the addition of fine aggregates possess to obtain 3D-printed objects with enough strength and resolution suitable for applications with conventional construction materials.

With the introduction of fiber-reinforced concrete in the application of 3D printing in construction, certain codes and standards are needed. Current standards in the building and construction industry are not suited for the new materials and technology [25]. Guidelines should be developed for the steel reinforcements in regard to the bonding between the rebars and the printed structure. Design codes should also be developed for the fiber-reinforced concrete, in particular, the mix ratio to ensure that the structure will not collapse due to the unsuitable concrete.

2.4 Design methods (BIM)

As mentioned earlier, to be able to 3D print any object, there is a need of a 3D model. In the construction industry, the most common software platform that is used is Building Information Modeling (BIM). BIM is defined as the use of information and communication technology to streamline the project lifecycle processes to provide a safer, more productive, and more efficient project [65]. The building is designed on the software, materials and costs are inputted resulting in an efficient project planning. Traditional construction projects have already adopted the software and are using it for design purposes [13]. The CAD file obtained from the BIM software should be converted to a machine language. The most common format is STL, which is named after the first technique for 3D printing, i.e., stereolithography. BIM can help to provide the required value judgments for creating a more sustainable infrastructure [65]. In construction, sustainable design is used to promote sustainability. Sustainable design aims to increase the quality of the built environment while reducing the negative impacts on the environment [66].

There have been studies performed regarding the use of BIM in construction automation; some studies investigated the development of new algorithms to convert as-built structures into the BIM software automatically [13]. The implementation of BIM in construction automation serves to make the construction process digital [67]. Two BIM software that are in use in the Architecture, Engineering, and Construction (AEC) industry are Autodesk Revit and Bentley Systems MicroStation [68]. For the BIM application in 3D-printed construction projects, the structural and mechanical properties, such as compressive strength and density, of the concrete must be specified and included in the BIM model [13].

The benefits of using BIM technology in 3D printing include an increase in productivity, efficiency, and quality as well as a reduction of costs and lead times [65]. Other benefits include fewer design coordination errors, more energy-efficient design solutions, faster cost estimation, and reduced production cycle times [3]. However, there are also challenges of the implementation of the software in construction. A study showed that only 46% of the respondents thought that construction safety was improved through BIM. This was due to the lack of BIM data specifically information about safety analysis [68].

2.5 Applications

There have been several 3D-printed building projects around the world in the past few years. Some companies that have constructed these types of buildings are Chinese company, Winsun; Danish company, 3D Printhuset; Dutch company, CyBe; a Russian company, ApisCor, and COBOD a German company. One of the first companies to step into the 3D printing construction industry was the Chinese company, Winsun. In 2005, the company invented the spray nozzle, which is one of the key components of the 3D printer. Experimentations were performed with the spray nozzle by using cement and other materials [69]. This company developed the first continuous 3D printer for construction in 2008 and in 2013 printed the first batch of 10 houses. The 3D printing occurred offsite in a factory and was then assembled onsite [10].

Winsun later on advanced to create other structures with the 3D printing technology including a six-story apartment building and a 1100-m^2 mansion. In Dubai, Winsun created the first 3D-printed office (Fig. 9) for Dubai Future Foundation, an organization developed with an aim to shape the future of the strategic sectors in cooperation with the government and private sectors [70]. The building parts were 3D printed in Suzhou (a city in China), cut into pieces, shipped to the UAE, and assembled onsite [69]. The construction took 17 days and labor cost was 50–80% lower than traditional methods. Furthermore, the construction waste generated was 30–60% lower than traditional methods. This type of offsite 3D-printed buildings can be considered as prefabrication as mentioned earlier.

In Europe, the first 3D-printed building was constructed in 2017 in Copenhagen by 3D Printhuset [24]. The idea came about because of the lack of 3D-printed buildings in Denmark and the rest of Europe. This issue was believed to be due to the strict building codes in Europe. The building was printed without having a single straight line except for the doors and windows. This was performed to show the geometrical freedom that 3D printing could have [71].

ApisCor is another company that has constructed 3D buildings. They claim to be the first company to develop a mobile 3D printer that is able to print a full building onsite. The company's mobile printer was used to print a 400 square foot home in Russia in 24 h [47] (Fig. 5). The total cost of the project amounted to 10,134 dollars [3]. The house was built during the coldest time of the year, and hence, there were limitations on the temperature allowed for the concrete. The geopolymer concrete used had the limitation that it could only be constructed above 5°; however, tents were used to solve the problem. The machine itself can operate down to negative 35 °C [71].

CyBe is a Dutch company that also claims to be the first company to develop a mobile concrete printer. This design is able to move on caterpillar tracks, which makes it easier to build on-site [72]. The company has executed several 3D-printed projects including an 80-m^2 one-bedroom house in Saudi Arabia; a bridge in the Netherlands; and the world's first 3D-printed laboratory.

More recently, in January 2019, it was announced that the world's longest 3D-printed concrete bridge has opened in Shanghai. A team from Tsinghua University School of Architecture built the structure, which is 86 feet long. It was produced in 450 h and Tsinghua University claims that it cost about a third less than a standard bridge of the same size [73].

Cobod, a European company, proposes modular 3D printers based on a gantry system. They claim that their printer is capable of printing a full 2-story building of 12 × 27 × 9 m [50].

3 Benefits of 3D printing in construction

AM in construction is a new technology being implemented, therefore there are still uncertainties in its application. However, it is a promising new technology and has many potential benefits. The benefits may be categorized into two groups: constructability and sustainability. Figure 10 shows the groups and their corresponding benefits, while Table 1 shows the main benefits along with their sources.

3.1 Constructability benefits

3.1.1 Faster construction

Time is an important factor for any construction project. Reducing construction duration adds many benefits to

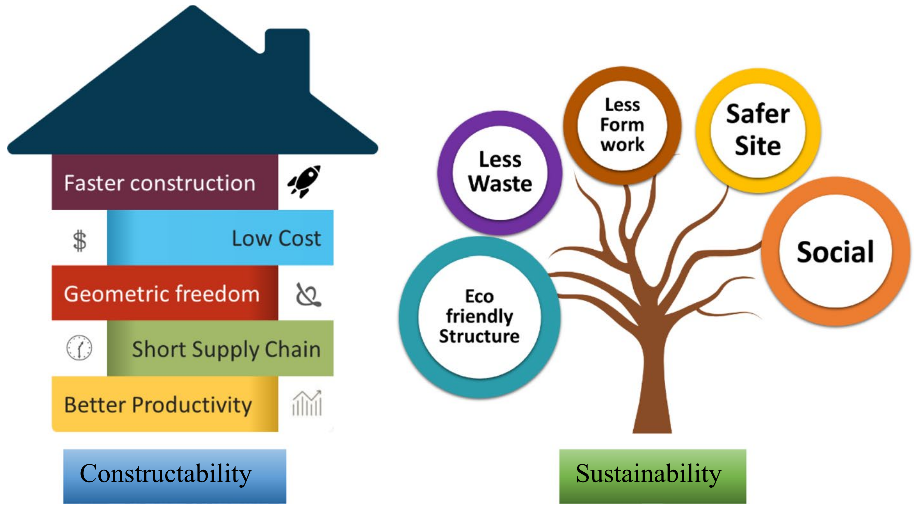


Fig. 10 Benefits of 3D printing

Table 1 Benefits of 3D printing in construction

S. no.	Description	Source
Constructability benefits		
1	Faster construction	[3, 10, 13, 16, 17, 25, 26, 48, 50, 52, 67, 72, 74, 93, 109]
2	Lower cost	[3, 10, 15–17, 25, 26, 43, 48, 50, 52, 67, 72, 109]
3	More geometric freedom	[13, 16, 17, 26, 28, 39, 48, 50, 52, 67, 72, 75, 76, 93, 109]
4	Shorter supply chain	[14, 26, 50, 75, 109]
5	Improve productivity	[17, 25, 43, 67, 77]
Sustainability benefits		
6	Sustainable and eco-friendly structures	[10, 26, 27, 43, 52, 67, 71, 72, 75]
7	Less waste	[10, 17, 25, 26, 28, 43, 50, 75, 83, 93, 109, 110]
8	Reduces formwork	[14, 25, 26, 50]
9	Safer sites	[10, 14, 16, 26, 28, 48, 84]
10	Social	[14, 17, 26, 67, 93]

clients such as starting the operations phase and generating revenues early, and reducing overhead costs and releasing resources for other projects. 3D printing provides the ability to construct faster. The speed of construction is much faster than traditional methods [3, 10, 72]. As mentioned in Sect. 2.5, a house can be printed in 24 h. This would increase the scale of construction and will aid in mass production. Many advantages are offered by automated building construction, such as superior construction speed and higher degree of customization [13]. Construction time can be greatly reduced using 3D printing technologies. For example, the printing time for a structural wall was reduced to 65 h from 100 h by 3D printing [17, 74].

3.1.2 Lower cost

3D printing reduces the cost of construction [17, 71, 72]. The cost of construction elements is reduced as well as the cost of transporting materials and storing them [3, 10]. Since the machine only requires one operator, the cost of labor is decreased. In the case of the 3D-printed office in Dubai, the laborers involved were seven workers to install building components, ten electricians, and specialists to handle the MEP and one worker monitored the printer. The labor cost of this office was 60% lower than traditional buildings of the same size [69]. Less labor-intensive operations in multiple segments of the Building and Construction industry was also noticed [48]. In addition to reduction in labor cost, 3D printing results in reducing the formwork installation and removal costs. Supervision cost will also be reduced as the number of site engineers, among others, will be reduced. Additionally, faster construction will reduce the indirect cost.

3.1.3 More geometric freedom

The technology allows for more geometrical and design freedom than traditional methods [17, 72]. Designing and constructing structures that would not be possible by other means is one of the advantages that spur interest in the technology [75]. The 3D-printed house in Denmark by 3D Printhuset mentioned earlier was built without straight lines, except for the doors and windows, to show the extent of the geometrical freedom. It is very easy to print the high-cost curved buildings that are hard to build in other ways. Thus, architects may have an open mind and make breakthroughs in the design process. Meanwhile, this helps realize the integration of architecture and arts [52]. The 3D printing process enables developers to design structures that are difficult to produce using the current manual construction practice [17, 76].

3.1.4 Shorter supply chain

3D printing allows shrinking the supply chain. By printing objects on demand, 3D printing eliminates lead time of materials that need expedited delivery [14]. This process hence increases productivity that would have been decreased by late deliverables [14]. Using raw earth materials also eliminates lead time of materials hence shortening the supply chain. AM of construction materials has been one of the emerging advanced technologies that aim to minimize the supply chain in the construction industry through autonomous production of building components directly from digital models without human intervention and complicated formworks [26].

3.1.5 Improve productivity

Construction automation has shown the potential to increase construction productivity [77]. AM is seen as a way of addressing construction productivity challenges [14]. The construction sector is under increasing pressure to improve its efficiency and effectiveness, reducing environmental impacts, material use, and costs [43].

3.2 Sustainability benefits

Sustainability is defined as the desire to carry out activities that meet the needs of the present without compromising the ability of future generations [78]. As mentioned in Sect. 2.5, in construction sustainable design is used to increase quality while reducing the negative impact on the environment. The LEED (Leadership in Energy and Engineering Design) rating system and certification is used in measuring the level of sustainability in a construction project [79].

3.2.1 Sustainable and eco-friendly structures

Implementing 3D printing in the construction industry will be sustainable and economically friendly [10, 72]. One of the reasons that it is eco-friendlier than traditional methods is the reduction of waste. Moreover, the concrete mix used in the 3D-printed house in Denmark contained recycled materials such as tiles and the walls were insulated with recycled cellulose fiber [71]. Moreover, the potential of using low impact materials such as raw earth materials and geopolymers adds to the sustainability of the structures. Perrot et al. [80] assessed the possibility of printing structures using earth materials. Results showed that with the addition of alginate to the earth materials, high productivity was achieved. A sample was prepared and the compressive strength was found to be comparable to traditional construction made with earth materials [80]. Geopolymers have also shown potential in improving sustainability. Zhang et al. [81] assessed the performance benefits and operational energy-saving potential of geopolymer foam concrete. Geopolymer concrete has a low cost and high strength/weight ratio. Additionally, WASP has built 3D-printed structures using geopolymer as mentioned in Sect. 2.4. A study also explored the potential of using geopolymers instead of Portland cement as a material for 3D printing. The carbon emission of geopolymers production is 80% less than Portland cement production [82]. CyBe [72] also claims that with 3D printing, the CO_2 emissions are reduced. This results in a significant decrease in the energy consumption in construction and an improvement in the production efficiency [52].

3.2.2 Less waste

The 3D printing technology reduces the amount of waste produced during construction [17]. Since the technology is a type additive manufacturing, the materials used are fitted to the output produced and therefore produce virtually zero waste [75]. Furthermore, 3D printing uses raw materials like sand that can be recycled and re-used [26]. It is estimated that 3D printing saves 30–60% of construction waste [28]. Wet construction processes are minimized, so that building erection process generate less material wastes and dust compared to traditional methods [10]. It provides a resource-efficient construction sector with lightweight structural components, which will help in reducing waste generation, emissions and global resource consumption [43, 83]. As only the required amount of materials will be needed, the printing process will eliminate unnecessary waste of materials, thus reducing the environmental impacts of the production/construction process [17].

3.2.3 Reduced formwork

Camacho et al. [14] also mentioned reduction in formwork as another benefit of AM. This process, which is needed in traditional construction, is eliminated, and hence the wastes that would have resulted from those formworks are disregarded. With AM construction, the structure is directly molded and formed on-site, without the need of wooden forms that regular concrete requires [50]. Reducing the use of formwork has an environmental impact as it reduces the amount of wood and therefore trees' use [14].

3.2.4 Safer sites

Safety is a major concern in the construction industry because fatalities and injuries from construction work bring great losses to individuals, organizations, and societies as a whole [84]. 3D printing reduces the number of injuries and fatalities onsite as the printers will be able to do most of the hazardous and dangerous works [10]. This benefit is because 3D printing allows for automation of the construction process. AM could provide services to the construction industry by reducing exposure of on-site workers to harsh environments and by automating some of the construction tasks [14].

3.2.5 Social

The use of 3D printing in construction projects has the potential to benefit the society in general as it changes the way the construction work is performed. It also induces changes in labor structures, including gender equality and plus safer working environment and generates shifts toward more digital and localized supply chains [26]. As most of the 3D printing process is highly automated, manpower required in the construction process can be significantly reduced [17]. Reducing the number of workers is one of the main benefits of 3D printing in construction [14, 26, 27]. This reduction in the workforce will introduce new types of construction workers who need new skills to cope with the changing technology.

4 Challenges of 3D printing in construction

The previous section discussed the several benefits of 3D printing in construction. As with any disruptive technology, 3D printing has several disadvantages. Social disadvantages include the negative effect on the existing construction workforce. 3D printing will reduce the need for large numbers of construction workers. Although this is considered a benefit as it reduces labor cost, it is also a disadvantage to those workers whose jobs will be at risk. That may create social problems in some communities that rely on construction activities. The quality of the final product also may be considered a disadvantage. The surface quality could be rough due to the printing process. At the current state of technology, 3D-printed buildings might not live up to the expectations of end users due to its design and material limitations. The size of the design is strictly constrained by the chamber volume of the 3D printer. Currently, 3D printing is not suitable for larger-scale projects. There are also geometrical limitations where the printer is restricted by specific possibilities. Another disadvantage is the cost, and currently, it is expensive to construct using 3D printing. The initial equipment cost may be prohibitive. The transportation cost of the printer is both challenging and expensive. One of the disadvantages is the material being used. The concrete should be workable to pass through the nozzle of the robot, this would require a specific type of concrete which might have lower quality and high costs. The limited availability of suitable material is considered a disadvantage. The disadvantages of requiring special material to be used in 3D printing are discussed further in the material-related challenges section. Implementing and advancing the use of 3D printing in the construction industry is still in its infancy stage and faces a number of challenges. Interdisciplinary work regarding the material science, computation, and design resulted in the development of a new method of 3D printing concrete material [39]. The challenges may be categorized into seven groups: material, printer, software, and computational, architecture and design, construction management, regulations, and stakeholders. The challenges are applicable to different 3D printing techniques with the exception of the printer category, which is limited to the extrusion-based technique. Table 2 shows the seven groups; their corresponding challenges, along with their sources. The main challenges found through the literature (Table 2) are material related. The most cited challenges are material printability, buildability, and open time.

4.1 Material-related challenges

This group includes the challenges that are related to the construction material such as printability, buildability and open time. The desired concrete for 3D printing requires certain specifications that are different from traditional construction; therefore, new materials have to be used in construction, because of the new technology requirements [10].

4.1.1 Printability

Printability refers to the ability of the material to be pumped and printed. Lim et al. [16] defined pumpability as the ease and reliability with which material is moved through the delivery system, and printability as the ease and reliability of depositing material through a deposition device. The material has to have the right consistency to be able to be pumped out of the nozzle of the 3D printer [17]. If the material is too hard, pumping it through the pipe to reach the nozzle would be hard and energy-consuming, and if the material is too soft, the precision for placing the material would not be accurate and would collapse easily. The rheological property

Table 2 Challenges of 3D printing in construction

S. no.	Description	Source
Material		
1	Printability	[10, 15–17, 27, 28, 48, 49, 52, 57, 67, 87]
2	Buildability	[16, 17, 26–28, 52, 57, 58, 67, 85, 86, 91]
3	Open time	[13, 16, 26, 27, 49, 57]
3D printer		
4	Scalability	[15, 26–28, 48, 57, 87, 91]
5	Directional dependency	[29, 57, 67, 88, 89, 103, 111]
6	Geometrical limitations	[29, 86]
Software related		
7	Cybersecurity	[28, 90, 111]
8	Interoperability	[10, 13]
9	Suitability of the digital model for printing	[10, 65]
Architecture and design		
10	Exclusion of building services	[17, 112]
11	Structural integrity	[13, 17, 27, 29, 46, 57, 112]
12	New design principles	[10, 25, 52]
Construction management		
13	Cost estimation	[15, 26, 27, 72, 87]
14	Construction site setup	[3, 4, 8, 14, 112]
15	Construction scheduling	[13, 14, 29]
Regulations and liability		
16	Lack of codes regulations	[26–28, 52, 69, 93]
17	Liability issues	[27, 28]
Stakeholders		
18	Skepticism of about the potential of 3D printing	[69]
19	Less demand for workers	[10, 14, 42, 75, 96]
20	New skills for construction workers	[14, 93]

and elastic properties evolution of concrete are essential factors affecting concrete printing in terms of buildability and pumpability [48]. The workability and the mix proportion of concrete plays a major role in the pumpability and printability of concrete [27]. To be considered good quality, the material must have the desired printability, to be able to be extruded from the nozzle, and buildability, to be able to maintain its shape [17, 57, 58].

4.1.2 Buildability

Lim et al. [16] defined buildability as the resistance of deposited wet material to deformation under load. The material should be quick hardening to be used in 3D printing [17]. Indeed, if the material needs an extended time to harden, it would collapse and would not hold its shape. 3D printing also has high requirements for construction materials. Due to the high speed of 3D printing, the materials have to solidify very quickly. Traditional construction materials fail to meet this need, and a special R&D job is required [52]. In addition, the concrete should bond together to form each layer and have sufficient level of buildability to enable it to lie down correctly, remain in position, and be stiff enough to support further layers without collapsing [17, 57]. Hence, the concrete has to support itself as it cures [85]. Because the material is extruded in a wet state, the build-up of layers must be in a manner such that they are self-supporting in order to avoid collapse, imposing somewhat of a restriction on possibilities for realizing some geometries [86].

4.1.3 Open time

Lim et al. [16] defined open time as the period where the printability and buildability are consistent within acceptable tolerances. Extrusion works particularly well when it is performed continuously, but problems such as over-printing (too much material deposited) arise when the material flow is interrupted and under-printing (a pause in deposition that does not coincide with nozzle movement) when restarting [16]. Special mixes are normally needed to obtain the material properties needed for additive manufacturing. For example, regular concrete would be unsuitable for AM for several reasons. Firstly, once the concrete is mixed, there is a limited time available during which it must be deposited; mixed concrete cannot be stored in a tank in a ready-to-deposit state. Secondly, regular concrete will not stay in place when multiple layers are deposited—it will slump under its own weight [49]. Printing of construction materials requires a mix formulation in which the setting time of the paste, shape stability of first few layers, and interlayer bonding between the layers, are thoroughly controlled and investigated [26]. For instance, any unexpected delay between depositions of successive layers could lead to the formation of structurally undesirable cold joints [13]. Moreover, the layer adhesiveness after deposition must be maintained in order to ensure that the structure will not collapse [27].

4.2 3D-printer-related challenges

4.2.1 Scalability

Scalability is a problem common to most existing 3D printing processes, where the size of the design is strictly constrained by the chamber volume of the 3D printer. This issue is more pronounced in the building and construction industry, where it is impractical to have printers that are larger than actual buildings [48]. 3D printing also faces a challenge since the technology is not ready for large-scale projects. Another issue is that automated construction is not suitable for large scale products [87]. Most existing 3D printing systems for building and construction are based on a gantry, which can only print structures whose sizes are at most as large as that of the gantry itself. Some arm-based systems have been demonstrated; however, the reach of the robotic arm limits the sizes of the printed structures [48]. Cable-based robots are proposed as an alternative to Gantry robots [39]. These robots are easier to install and less costly than Gantry robots; however, their control is relatively complex.

4.2.2 Directional dependency

Directional dependency is believed to be an attribute of layered manufacturing process, hence 3D printing [88]. The printing direction has a major influence on the load-bearing capacity and strength properties of the material [89]. Most 3D-printed geometries require a filament to be linear deposited. Filament has a direction, and therefore creates the issue of directional dependency [29]. Compared to traditional construction that uses cast iron, the printed specimen has mixed isotropic and anisotropic properties in different directions, whereas cast specimens have isotropic properties in all directions [89].

4.2.3 Geometrical limitations

Although 3D printing provides geometrical freedom, it also has its limitations. 3D printing seems to imply that a CAD file can be produced independent of process planning; however, this is not true for 3D concrete printing. The method of printing is limited by specific geometrical possibilities [29]. One example of a geometry not achieved with 3D printing that can be achieved by traditional methods is straight edge corners. Moreover, the obtained dimensions have some errors compared to the ideal ones set in the CAD model. These errors can have several sources, where the accuracy of the robot system is the main one.

4.3 Software-related challenges

Most of the research focuses on the material and the robotics challenges related to 3D printing in construction. However, software-related challenges are also important. New software platforms are also highly essential for realizing a fully automated and reliable building construction system [13].

4.3.1 Cybersecurity

Since the construction process is automated and all pieces of information are in the 3D model, cybersecurity and risk of hacking pose a threat [28]. There is a concern for the security of the storage, transfer, and execution of the 3D models; AM is at risk of outpacing the necessary security infrastructure needed to ensure safety [90].

4.3.2 Interoperability

Data interoperability ensures that all disciplines will work efficiently together with the same information representing the designed model [13]. 3D printing faces this challenge since all processes are made digital; therefore, there is a need to ensure interoperability of the applications used at the architectural design, structural analysis, and printing process [10].

4.3.3 Suitability of the digital model for printing

In order to automate the building process to manage and optimize it, translation of the digital model and verification of its suitability for printing process must be performed with minimal human intervention, most desirably fully automatic [10]. Moreover, substantial time is needed to create digital models for 3D printing [65].

4.4 Architecture and design-related challenges

4.4.1 Exclusion of building services

Exclusion of building services also creates an issue. Building services like electric sockets, plumbing, and door and window opening are not integrated in the design process yet. In two Winsun projects, one of the obstacles faced was that building services such as electrical and plumbing were not integrated in the 3D printing process. Therefore, additional work had to be conducted, causing problems to the structural integrity [17]. Additional work should be performed in providing openings for these MEP components. However, some companies claim that 3D printing allows "already integrated components into built structures, such as plumbing into printed walls." This shows that continuous research is being performed to overcome all the challenges and barriers faced with 3D printing in construction [56].

4.4.2 Structural integrity

The quality of the printed parts has been found to be brittle and therefore has faced problems in printing load-bearing components [91]. Good quality concrete is essential in ensuring a successful 3D-printed building. The key question is whether a generic strategy can be developed to obtain sufficient robustness and ductility for structural applications [29]. The layered structure is likely to be anisotropic as voids can form between filaments to weaken the structural capability [55]. The bond between filaments, as well as between layers, probably influences the hardened properties of concrete components [55]. Bonding between layers in 3D printing is critical in many applications especially in 3D printing of concrete [46]. Therefore, a high strength in compression and flexure as well as tensile bond is the main target in developing this concrete. Additionally, a low shrinkage is essential as the freeform components are built without formwork and this could accelerate water evaporation in the concrete and result in cracking [55]. The non-availability of course aggregates may also increase the potential for shrinkage and cracking.

With a rapid increase in additive manufacturing and rapid prototyping in construction, there is a great interest in enhancing the structural integrity of the 3D-printed structure [46]. Crack formation and propagation play an important role in the structural performance of contour crafted walls, and the location of bond failure will aid in the investigation of the stress zones at interfaces [46]. Various studies found that the strength and stability of the printed products using current printing materials (such as plaster) might prevent the technology from being used in large-scale models or buildings [17].

4.4.3 New design principles

Using 3D printing in construction requires also a change in the way architects and engineers design. AM will cause a shift in the design and manufacturing process due to its capability of manufacturing geometrically complex and customizable products [25]. Moreover, since the material used in AM is different from traditional projects, it should be taken into consideration in the design process [52]. Since nozzles are used to transfer materials in 3D printing construction, the design should comply with the features of pressure and mechanical modeling [52]. Several authors [55, 80, 92] investigated the effect of nozzle shape and size on the extrudability of the mix. Shakor et al. [92] compared the results of 3D-printed objects obtained by a circular nozzle and a rectangular one. They showed that a rectangular or square shape yields a better-printed object than a circular nozzle. The used criteria were the flexural strength and consistency of the results. Similar conclusions were reached by Perrot et al. [80] when investigating the processing aspects of earth-based materials. The design should comply with relevant construction standards. Existing architectural systems cannot be used, and therefore, a new architectural design system should be created to comply with the requirements of 3D printing [52]. The concept of contour crafting, allowing in-situ printing of dwellings may require the new architectural approach to building design [10].

4.5 Construction management-related challenges

4.5.1 Cost estimation

The use of 3D printing creates a new challenge in an important construction management function, which is cost estimation. Since it is an emerging technology, it is a challenge to estimate the construction cost with the required accuracy. Additionally, the technology is associated with a high initial cost. This cost might reach as high as 250,000 Euros [72] and therefore it might cause uncertainty in buying the product, however, this is only an initial cost and the construction cost while using the printer would be much less than using traditional methods. Ghaffar et al. [26] mentioned that large-scale printers are expensive and the need for ongoing maintenance increases the cost. However, this price is expected to go down due to industrial competition.

4.5.2 Construction setup

Most construction sites are challenging for AM since they do not provide a controlled environment. Another issue is the transportation and setup of the equipment at the building site; its ability to adapt to different applications with different geometries, access levels, and underlying materials also creates an issue [14]. The transportation cost of the printer on-site can be difficult and expensive due to the size of the printer [3]. The current on-site fabrication AM systems still require that certain environmental conditions be met for best results or that a type of enclosure is provided to keep desirable temperatures [14]. A material preparation and delivery system are also required to provide continuous feed to the nozzle [13]. Bock [4] mentions that overtime the ability of robot systems has grown and that they can operate in "comparably unstructured environment". This shows that by time and with research, construction site setup will be easier.

4.5.3 Construction scheduling

The use of 3D printing in construction projects requires new skills and techniques in construction scheduling. The new construction schedule will have to include the traditional scheduling techniques in addition to machine scheduling. Machine scheduling is complex since the directional dependency has an impact on print strategy. In addition, most of the printing activities will be continuous while normal construction schedules consist of discrete activities [29].

4.6 Regulations and liability-related challenges

4.6.1 Lack of codes and regulations

Lack of regulations of 3D printing in construction also creates an issue. There are no set regulations for the use of 3D printing in construction and therefore it would be difficult to use the technology in a way to abide by all the construction codes and guidelines. AM might have implications on existing laws and regulations and therefore require adaption of the laws to include AM or the creation of new laws. Efforts are being made to change these regulations to include 3D printing [27]. In China, some companies are working with the Chinese national construction standards department to amend the construction guidelines to include 3D printing. [69]. The current 3D-printed building structures are experimental, as further characterization of print materials, clarification of construction practices and printing processes, and integration into current building code regulations are required [93].

4.6.2 Liability issues

Different people from different companies are responsible for the development of 3D-printed objects. In cases of accountability and liability, there is an issue of who would be responsible in case of failure [28]. A clear legal framework should be developed in order to identify the persons responsible for an accident [27].

4.7 Stakeholders-related challenges

4.7.1 Skepticism about the potential of 3D printing

Research performed on sustainable construction projects showed that resistance from clients to adopt new green ideas was a challenge [94, 95]. There is also skepticism of designers, clients, and contractors about the potential of 3D printing in construction. The lack of knowledge about technology is also a barrier [69].

4.7.2 Less demand for workers

There is less demand for labor when constructing a building using a 3D printer. The technology invades the construction work that is typically performed by human workers [96]. It can be an advantage in regards to labor cost; however, this new technology will decrease opportunities for several people in the construction industry. Some authors mentioned that reduced need for labor could be politically destabilizing for some economies [75]. A major obstacle has been that the construction industry is steeped in high-skill, labor-intensive conventional processes, not conducive to adaptation of automation technologies [42].

4.7.3 Need for new skills for construction workers

The use of 3D printing in construction requires new skills for construction workers. These new skills include the installation, operation, control and maintenance of the 3D printers. These new skills, which are essential in ensuring a successful project is not readily available on a typical construction site [93]. The use of AM in construction lowers the demand for labor; however, at the same time, it opens new opportunities for jobs with different skill sets than the ones needed in traditional construction [14].

5 Risks of 3D printing in construction projects

Although the use of the new technology may reduce some construction risks due to the reduction of the number of construction workers, it may bring additional risks. As discussed in Sect. 4, there are several challenges related to the use of 3D printing. These challenges can create risks for the construction projects. The risks may be categorized into seven groups: 3D printing material, 3D printing equipment, construction site and environment, management, stakeholders, regulatory and economic, and cyber

Table 3 Risk categories for 3D printing in construction

S. no.	Description	Source
1	3D printing material risks	[13, 16, 17, 24, 26, 46, 86, 91, 94, 97, 98]
2	3D printing equipment risks	[22, 24, 66, 72, 94, 99–102, 113, 114]
3	Construction site and environment risks	[3, 14, 20, 21, 94, 99, 102, 115–117]
4	Management risks	[13, 21, 22, 69, 94, 97, 104–107, 114, 116–120]
5	Stakeholders risks	[17, 22, 69, 94, 97, 98, 114, 116, 117, 121]
6	Regulatory and economic risks	[21, 69, 79, 94, 97, 102, 104–107, 116, 119, 120, 122, 123]
7	Cyber security risks	[28, 90, 108, 111]

security risks. Table 3 shows the main risks along with their sources.

5.1 3D printing material risks

3D printing in construction requires special material that has three main characteristics: printability, buildability, and open time. This new material will come with its own additional risks. The required concrete might cost more than traditional concrete and this would add additional costs.

The lack of buildability arises because material is extruded in a wet state, and hence, the build-up of layers must be such that they are self-supporting in order to avoid collapse [86]. Any unexpected delay between depositions of successive layers could lead to formation of structurally undesirable cold joints [13]. Moreover, inappropriate open time is a risk since printing of construction materials requires a mix formulation in which the setting time of the paste, shape stability of first few layers, and interlayer bonding between the layers should be controlled [26].

Lack of specified printable quality can be caused by two opposite extremes. Extrusion works particularly well when it is performed continuously, however, lack of this continuity results in problems such as over-printing and under-printing. Over-printing occurs when too much material is deposited due to the material flow being interrupted. On the other hand, under-printing occurs when there is a pause in the deposition that does not coincide with the nozzle movement and is caused when restarting [16]. This risk could also be categorized as equipment-related risk (feeding).

Lack of buildability, printability, and inappropriate open time of the material causes poor material quality and performance [94, 97]. Some studies have shown that 3D-printed concrete can have a low quality (brittleness) [91]; however, research is being performed to produce high strength concrete suitable for 3D printing [17]. As of now, poor quality of the 3D-printed concrete poses a risk to the completion of a successful and high-quality project [91]. As for the performance of concrete, bonding between printed layers is critical. A series of preliminary experiments on layered concrete fabrication show the vulnerability of the structures due to low strength at bond interfaces [46]. Another risk related to performance arises from faulty material deliveries, that may affect the performance of the 3D printer, and inappropriate handling and storage of 3D printing materials, which would lead to construction wastes as found in a study performed on the material waste in the UAE construction industry [98].

5.2 3D printing equipment risks

The 3D printing equipment may raise significant risks in construction project. An important measure of the printer performance is robustness [49]. The initial cost of the equipment is high, compared to other machinery used in construction. This additional cost due to 3D printing equipment creates a risk for the project [72]. Handling of the 3D printer is crucial in ensuring that no damages occur. The fact that the printer has to be imported adds to the risk and makes it more critical, since any damages that occur would prolong the completion date and add additional costs [98].

3D printers pose malfunctions and hazards including mechanical, electrical and chemical. Electrical components of the robot could be of low quality and hence create electrical hazards [99, 100]. Injuries caused by machines are ranked among the top industrial accidents [99]. Chinniah [101] mentions the risks associated with industrial robots that include robot malfunctions and human error while using the robot. Workplace health and safety Queensland (2015) also points out these risks by mentioning mechanical hazards such as cutting, crushing, and entanglement. Furthermore, human mistakes through interference with the technology can be costly [99–101].

5.3 Construction site and environment risks

The construction site and environmental factors pose additional risks to the construction project. Site complexity creates a difficult working environment for robots [102]. The 3D printer works under conditions where the surrounding environment is predictable; the ideal workplace environment for the robot should be ventilated and space should not be confined [99]. However, in the case of the site, the printer needs to adapt to different access levels and underlying materials [14]. Unforeseen site conditions may delay construction work and result in cost overruns. There is also the risk of transportation of the 3D printer onsite. Due to the large size of the printer, the transportation would be costly [3]. Therefore, this increases the risks of delays during transportation and equipment setup. The current onsite fabrication AM systems still require that certain environmental conditions be met for best results or that a type of enclosure is provided to keep desirable temperatures [14]. The robots might not work efficiently at extreme temperatures [99]. Moreover, extreme weather such as sand storms, snow, extreme winds can cause damages during construction [103].

5.4 Management risks

Improper project feasibility and planning is a risk in all construction projects and is magnified in 3D construction due to the unfamiliarity with the new technology. Project feasibility and planning has to be conducted in an accurate manner to ensure the successful completion of the construction project [95]. Another risk is the inaccuracy in project budgeting. This risk is due to the lack of information and knowledge about 3D printing in construction [94]. Construction project managers are usually the individuals who know the most in a construction project. What would occur if the project manager has poor skills in handling 3D-printed construction project? This is a risk and all project managers, who are responsible for a 3D-printed project, should be able to know all the appropriate information and knowledge [97].

The risk of poor quality of construction work is typically allocated to the contractor, as the quality of work is their responsibility [104]. This risk has been found to be one of the key risks in the Chinese construction industry [105] and the UAE construction industry [21].

Owners tend to rush projects, which results in poor scope definition. The definition of scope contains the overall benefits and project objectives [106]. Poor scope definition creates a risk because it may affect project objectives [21]. Inaccuracy in construction schedule due to unfamiliarity with 3D printing is an important risk. Construction schedules (activity durations and logic) are normally prepared based on experience and past projects. The available information on 3D printing in construction is rather limited. This may result in an inaccurate construction schedule.

5.5 Stakeholders' risks

The general or stakeholder's risks include the actions or decision made by the stakeholders of a construction project. The stakeholders include the owner, contractor, designer, subcontractors, suppliers, workers, and others.

Resistance from client to adopt new ideas is usually a risk for projects that execute concepts that conflict with the traditional method. Hwang et al. [94] mentioned that resistance from the client to adopt new ideas, in this case sustainable construction, was a risk. Clients usually stick to the ideas and methods that they know and are familiar with, which creates hesitance in adopting new construction techniques [94]. A case study performed by the Boston Consulting Group for the World Economic Forum demonstrates that the skepticism of clients, designers, and contractors creates a challenge and a risk in adopting 3D-printed construction techniques [69].

In a survey performed on the risks of a new technology introduced in a nuclear power plant. "Lack of knowledge of the new technology" was the second risk identified in the top 10 based on level of significance on project objectives [22]. Moreover, it was found that in highway construction projects in Chinese market, usage of emerging technologies is critical [97].

Another risk is the shortage in labor skilled in 3D-printed construction. Finding labor force that is skilled in 3D-printed construction is very challenging, especially in developing countries where these techniques are not yet adopted. Therefore, the shortage in labor skilled in 3D-printed construction is a risk. Shortage of labor skilled in modern technologies was in the top 10 risks found in sustainable construction projects in Singapore [94].

There is the challenge of finding suppliers of such concrete. Therefore, there is a risk of shortage of 3D printing material and suppliers [17]. Similar to limited availability of 3D printing concrete supplier, 3D printers' suppliers are also limited. 3D printers for construction are not available everywhere and there are very few suppliers around the world (Namely CyBe, 3D Printhuset, and Apis Cor). Companies would most likely have to import this equipment and this would create additional cost and risk [94].

5.6 Regulatory and economic risks

Lack of codes and regulations regarding 3D printing in construction is a key risk. This is due to the technology being new in the construction industry and there are limited sources and a small number of projects that have been constructed. Moreover, changes in construction codes and regulations are another risk. This risk is because some of the changes made may occur during the construction phase and these changes may affect the completion of the construction project. In a survey performed on risk management in construction projects in developing countries, changes in the law and regulations came up to be the second most critical risk out of 28 total risks [107].

Government approvals and building permits have to be obtained before the start of any construction project, and delays in government approvals may lead to a delay in project completion [21]. Inflation of material prices has been an issue for a long time. This is the first ranked risk in the UAE [21] and Singapore [94]. Difficulty in claiming insurance is another risk. Insurance might not cover the use of the technology since it is 'unproven' [102].

5.7 Cybersecurity risks

Cybersecurity risks include all risks related to the breach of the network by hackers. This includes design theft, digital sabotage, and network breach. Cybersecurity risk is defined as the potential financial loss, reputational damage or business interruption due to improperly secured data held within information systems [108]. Since 3D printers use data from a CAD file, there may be a risk that the information system is hacked. Some hackers may steal the design file and use it. Others may modify certain parameters that would affect the printing process. Hackers may also introduce viruses in the network that would interrupt the work and cause delays [108].

6 Recommendations and concluding remarks

6.1 Recommendations and future research

The effort to design efficient systems to deal with large-scale 3D printing is growing. However, all the industrial applications are limited to two different structures, i.e., Gantry and articulated robots. Lately, some new architectures, based on cable robots, are being tested. These structures are promising as they can easily deal with large-scale constructions and they are easy to setup and transport. However, the biggest challenge facing the use of 3D printing in construction is by far related to the materials to be used. This problem is related to the nature of the classical constructed buildings, which are using reinforced concrete, and the ability of 3D printing to incorporate these reinforcements in the process. Most of the research is oriented toward the use of high strength concrete, which is still not up to the standards required for a reliable construction. To overcome some of the challenges brought up by existing materials, more research is needed to develop new construction materials that are suitable for 3D printing fiber-reinforced concrete can be a good solution [92]. Another direction is to investigate the possibility of printing multimaterial simultaneously with multiple nozzles.

Some of the design-related challenges could be solved by introducing innovations. For example, a solution to the exclusion of building services is to integrate the MEP openings in the design of the model and operation of the 3D printer. Furthermore, architects and engineers need to adapt their designs to the limitations of the 3D printer. Adapting the CAD model to the limitations of the robots is a key solution to obtaining high-quality 3D-printed building. 3D printing robots of the future will be required to reach new heights to be able to print tall buildings. The future research will address the large-scale structures and new designs, e.g., cable robots, mobile robots, and will be the future systems for 3D printing. Cybersecurity challenges and risks are significant and require software companies to develop solutions that minimize hacking and offer multistep authentications before printing commence to ensure that it matches with the original design. Building codes and regulations are in great need and initiatives in some countries are already taking place.

Apart from the technical solutions, there is a need for construction and project management innovations to address the new challenges. 3D printing allows for reducing construction time and cost, as well as waste. Project managers should change their way of planning and scheduling. There is a need for integrating project scheduling with machine scheduling to ensure the smooth operation of the 3D printer and the normal construction activities. More research needs to be performed regarding risks. 3D printing-related risks need to be assessed in terms of probability and impact and risk response strategies need to be developed.

There is still a long way to go for this technology to replace existing construction methods especially for large projects. Major stakeholders need to work together to address these identified challenges. Governmental entities and professional organization need to establish codes and regulations. Structural designers need to study the structural integrity aspects of 3D-printed structures while material engineers need to continue developing 3D printing materials that have the three main characteristics: printability, buildability and open time. Architects and designers need to consider the new possibilities offered by the 3D printing technology and innovate their designs to suit the possibilities and limitations of the new technology. Construction management professionals have an important role to play as the new technology poses several challenges related to construction, scheduling, cost, risks, among others. Robotics engineers also need to address the challenges related to scalability. Software engineers need to improve the cybersecurity of these new systems.

6.2 Concluding remarks

Research in the area of Additive Manufacturing, and in particular, Additive Manufacturing for construction, is very rich, as it can be seen from the high number of references cited below. This paper offers a comprehensive review of literature related to 3D printing in construction. It addresses an identified gap in similar review papers and offers a broader coverage of technical and managerial challenges. The paper identified twenty challenges and classified them into seven categories. Similarly, risks are identified and classified into six categories. This covers an important literature gap and offers new directions of research focusing not only on the technical aspects but also on the managerial aspects. Additionally, the paper discusses and evaluates the different systems of 3D printing in construction. Based on the reviewed literature, the main conclusions are as follows:

- 3D printing has the potential to revolutionize the construction industry. 3D printing, along with advances in Industry 4.0, has a high potential to lead to a more efficient and sustainable construction.
- Despite the major advances in 3D printing technology, as reported in the literature, the application of 3D printing in construction is still in the infancy stage. There is a long way for it to reach its potential and warrant a widespread implementation. Research is still underway in several areas especially in the robotic and material aspects.
- The main challenge is adapting the robotic system to large scale construction projects such as villas and high-rise building. Normally, the robotic system is tailored to small and confined workspace. In construction, the robotic system needs to be adapted to a larger and more open workspace.
- 3D printing requires specific material properties. Most reviewed research focused on meeting the constraints of the 3D printer. However, more research is needed to meet the design and strength constraints in addition to the 3D printer constraints.
- The limitations of the 3D printer technology, the quality of the final product, and the complexity of the construction process are the main reasons for the low adoption rate of 3D printing in construction.

3D printing will definitely be part of the future of the construction industry. However, several challenges still need to be addressed before 3D printing can become a viable solution. Risks associated with this new technology were identified and classified based on their sources. These risks need to be assessed, in order to consider them during the planning stage of the construction project.

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