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A critical review of 3D printing and digital manufacturing in construction engineering

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Abstract

Purpose: In recent years, 3D printing technologies have been widely used in the construction industry. 3D printing in construction is very attractive due to its capability of process automation and the possibility of saving labor, waste materials, construction time, and hazardous procedures for humans. Significant researches were conducted to identify the performance of the materials, while some researches focused on the development of novel techniques and methods, such as building information modelling (BIM). This paper provides a detailed overview of the state-of-the-art of currently employed 3D printing technologies in the construction areas and global acceptance in its applications.
Design/methodology/approach: The working principle of Additive Manufacturing (AM) in Construction Engineering (CE) is presented in terms of structural design, materials used, and theoretical background of the leading technologies that are used to construct buildings and structures as well as their distinctive features.
Findings: The trends of 3D printing processes in CE are very promising, as well as the development of novel materials, will gain further momentum. The findings also indicate that the digital twin in construction technology would bring the industry a step forward towards achieving the goal of industry 5.0.
Originality/value: This review highlights the prospects of digital manufacturing and the digital twin in construction engineering. It also indicates the future research direction of 3D printing in various constriction sectors.

Keywords: Additive manufacturing, rapid prototyping, 3D printing, additive construction, concrete printing

Paper type: General review

Nomenclature/abbreviation

ABS = acrylonitrile butadiene styrene;

AC = additive construction;

AM = additive manufacturing;

AMIE = Additive Manufacturing Integrated Energy;

BAAM = Big Area Additive Manufacturing;

BIM = building information modeling;

CC = Contour Crafting;

DED = directed energy deposition;

DMLS = direct metal laser sintering;

DM = Digital manufacturing;

DT = Digital twin;

EBM = electron beam melting;

GMAW = gas metal arc welding;

ORNL = Oak Ridge National Laboratory;

PDF = powder bed fusion;

SBA = selective binder activation;

SOM = Skidmore, Owings, & Merrill LLP;

SLM = selective laser melting;

SPI = selective paste intrusion;

SSS = selective separation sintering;

3D = three dimensional;

1. Introduction

Additive manufacturing (AM) technology (also known as 3D printing) produces objects in a layer-by-layer method directly from the 3D model. It has been rapidly evolving since it was first invented. It has already been utilized in various industries such as aerospace, automotive, energy, and biomedicine industries facilitating the fabrication process from a digital model to ready-to-use final products (Vaezi and Chua, 2011, Hager *et al.*, 2016). In addition, AM creates 3D geometries and structures from digital files. Computer-Aided Design is the main tool to design digital prototypes, which will be printed layer by layer of remarkably thin cross-sectional areas. This process enables to manufacture of complex geometries and surfaces that are comprehensive to achieve by conventional tools (Jandyal, 2021).

AM is becoming attractive in the construction industry, owing to a narrow range of building automation systems in situ in materials and technological procedures (Duballet *et al.*, 2017, Sakin, and Kiroglu, 2017). Additive manufacturing or 3D printing technologies used in constructing buildings are also known as additive construction (AC) (Labonnote *et al.*, 2016). AC also provides possibilities for building extraordinarily complex geometries, giving designers and architects opportunities to think freely without putting themselves into specifically limited frames (Lloret *et al.*, 2015).

Generally, the first attempts of automated construction were conducted by a team of researchers and robot manufacturers sponsored by the Japan Industrial Robot Association in 1978 (Taylor *et al.*, 2003). In the next 20 years, the group had developed more than 550 autonomous construction systems. In these systems, robots were applied successfully for various construction works such as concrete floor flushing, spray painting, materials handling, and tile inspection. Nevertheless, in the late 1990s, the first proposed studies of 3D printing in construction were appeared (Pegna, 1997). As a result, 3D printing has been started to expand its applications as an automated system in many industries, including construction engineering, which is considered one of the largest consumers of non-renewable resources and natural materials worldwide (Ibrahim, 2016).

Traditional construction engineering has many challenges, such as work in harsh environments, shortage of a skilled workforce, safety, waste of materials, and transportation of materials (Delgado Camacho *et al.*, 2018). Importantly, safety in the construction area is one of the main challenges because construction sites are extremely hazardous (Zhu *et al.*, 2016).

Therefore, the opportunity to implement automated additive construction systems in situ will allow us to solve these problems in the shortest possible time, increasing interest in such technologies.

The progress of additive manufacturing possesses a promising direction in the civil engineering industry. AC minimizes human participation, resulting in eliminating many construction hazards (Ibrahim, 2016). Additionally, the reduction in labor that AC provides would also decrease the cost (Holt *et al.*, 2019). Moreover, additive manufacturing technology decreases environmental harm during construction, such as waste and noise pollution, to reduce the need for formwork usage (Tay *et al.*, 2017, Kothman and Faber, 2016). According to Lawson, the construction industry generates 53.5 Mt of construction and demolition wastes (Lawson *et al.*, 2001). The previous studies showed that additive manufacturing could decrease 30-60% of construction wastes, 50-80% of labor costs, and 50-70% of production time (Doris, 2016). For instance, WinSun Company used construction and industrial wastes and dumps instead of new building materials for their 3D printed houses (Busta, 2016). With the help of computer simulations in the construction of these houses, it was able to lay connectors for insulation, electrical wiring, and windows. All these items could be installed after the completion of printing.

The development of 3D printing using cementitious materials in construction has been stimulated by prints using polymeric materials and the high cost of shuttering, which affects the final building construction costs (Rubio *et al.*, 2017). Three steps need to be followed to prevent printed materials from being dashed or self-compacted. The material should be extruded through the extruder heads in the first one, maintaining its form after being deposited. In the next step, layers should not be degraded or collapsed when the following layer is being deposited. And in the last step, a proper bond between layers should be assured (Panda *et al.*, 2017a, Kazemian *et al.*, 2017).

Detailed analysis and review of the 3D printing in construction are challenging because of commercial reasons competitors do not publicly share the details of their printing systems, materials compositions, and other information (Bos *et al.*, 2016). Nevertheless, this paper presents an up-to-date overview of additive construction based on publicly available works published from 1997 to 2020. The rest of the paper is organized as follows; section 2 describes various types of materials used in construction engineering, section 3 highlights the available types of 3D printers used in CE, section 4 explains the theories and technologies in CE, section 5 discusses Digital Twin (DT) and Digital Manufacturing (DM) in CE, section 6 highlights the obstacles in utilizing 3D printers in CE, section 7 foresees the future of AM in CE, section 8 briefly concludes the overall findings.

2. Types of construction materials in 3D printing

Different materials can be used in construction 3D printers, but the most widespread types are concrete materials followed by polymers and metallic materials.

2.1 Concrete materials

Concrete is the most widely used material in building construction due to its mechanical strength, low production cost (Bos *et al.*, 2016), local availability, mouldability into different shapes, high thermal resistance, and excellent durability (Paul *et al.*, 2018, Buchanan and Gardner, 2019). The mixture used for concrete 3D printing should possess less viscosity and has large yield stress

(Panda *et al.*, 2018b, Le *et al.*, 2015). In addition, it is highly reliable in compression, fire-resistant, and highly durable (Bos *et al.*, 2016), and possess lesser environmental effect (Alhumayani *et al.*, 2020). The widely used materials as concrete are cement-based (Geneidy *et al.*, 2019, Shakor *et al.*, 2019). Concrete printing is a more widely used and more advanced technique in additive construction than printing with other materials (Buchanan and Gardner, 2019).

Concrete materials are used as the "ink" or "filament" of a 3D printer, in which concrete material can easily be extruded via the extruder system. The workability of the system is dependent on the mix proportion and materials selection. Adequate adhesion and rigidity are essential to get successful printing results without any failure. Besides, in concrete AC, the setting time of the first layers affects the mechanical strength of the structure (Zhang *et al.*, 2019, Perrot *et al.*, 2016).

Some researchers attempted to print concrete with fiber reinforcement to reduce steel materials used in 3D printed buildings. Hambach *et al.* (2019) proposed a novel composite of Portland cement paste and aligned glass, basalt, or carbon fibers. They tested the mechanical properties of 3D-printed parts. According to their obtained results, adding a 1.0 volume % fraction of carbon fibers to the cement can further increase the cement pastes' flexural strength. However, reinforcement did not considerably alter the compressive strength of the objects. Soltan and Li (2018) investigated the new state rheological properties of self-reinforced cementitious composite materials. They reported the effects of compositional elements and process parameters on early-stage properties. Shakor *et al.* (2020) studied the effects of deposition nozzle's velocity on the printed mortar's width and slurry properties, including Portland cement, fine sand, chopped glass fibers, and chemical admixtures. They found that the mechanical strengths of the printed specimens were reduced due to the voids and pores, which can be appeared as a result of printing methods and printing parameters. Hence, further development of printing methods and parameters is required to decrease voids and pores in the printed materials.

Le *et al.* (2012) studied the mix design and new properties of high-performance reinforced printing concrete. They found the optimal material fraction selection of each ingredient with validations. The optimal result was achieved when the nozzle diameter was 9 mm, the sand-binder ratio was 3:2, the water-binder ratio was 0.26, and the superplasticizer and retarder were 1% and 0.5%, respectively.

The stone sludge has been aggregated to produce Eco-Bricks concrete to decrease the waste produced during stone cutting and polishing processes (Rajgor and Pitroda, 2013). 3D printing using stone slurry has been used to create architectural structures in Italy by Desamanera Company (Stone-ideas, 2017). In another project Novi 3D print mechanism has been developed, which uses limestone wastes as the material for construction purposes to reduce the waste produced during construction (Biltcliffe, 2016). Application of stone sludge for 3D printing material purposes can bring lots of benefits in terms of waste reduction, reduction of shuttering, time and cost employed in construction, and the overall promotion of automatic construction (Annappa *et al.*, 2021).

Xia and Sanjayan (2016) proposed a novel method for formulating geopolymer-based materials for the commercially available powder-based 3D printers' requirements. As the result of this study, it was shown that the prepared material is applicable in 3D printing, and printed objects had good geometrical accuracy and sufficient strengths. Furthermore, the authors concluded that this type of 3D printing approach could be perfectly suitable for construction applications, providing additional enhancements in strength.

2.2 Polymers

Polymers are the most popular materials used in conventional 3D printers because of the low price and equipment availability (Furet et al., 2019). However, polymers usage in AC is characteristically limited in applications to facades, mechanical and electrical systems. Therefore, there are only a few examples of construction projects that used AC for polymer printing.

Generally, due to the highly flammable properties of polymers, the application of the material in AC is restricted. Therefore, Vahabi et al. (Vahabi et al., 2021) studied the application of flame retardant polymers in AC. They found that creating some pores inside the material can improve thermal conductivity and diffusivity. Moreover, since 3D printing can generate layers with different properties, the addition of flame retardant materials to the layers reduces the flammability of the material. The University of Tennessee, collaborating with Skidmore, Owings, & Merrill LLP (SOM), used the BAAM system to work on the Additive Manufacturing Integrated Energy (AMIE) demonstration project (Biswas *et al.*, 2016). AMIE was prepared to show as an example of the capabilities of 3D printing in construction engineering that the system can manufacture energy-efficient buildings with less material waste. Moreover, this particular project demonstrated the need and benefits of interdisciplinary research and collaboration with industry (Biswas *et al.*, 2016).

Furet et al. (Furet *et al.*, 2019) proposed a novel process of creating complex walls by 3D printing materials using a movable robot. The technology consists of printing two polyurethane foam walls placed onto both sides of a concrete wall. These polymer walls provide excellent insulation without using thermal bridges.

In Amsterdam, a canal house was constructed by joining 3D printed plastic blocks initiated by DUS architects. The company developed its 3D printer with a printing size of 2.2×2.2×3.5 m to print polymer block, weighing 180 kg (Wu *et al.*, 2016).

2.3 Metallic materials

3D printing with metal materials has already been used in many industries, such as aerospace, oil and gas, automotive, and energy industries (Duda and Raghavan, 2016). Additive manufacturing with metals can be divided into two groups: (i) powder bed fusion (PBF) technologies and (ii) directed energy deposition (DED). The leading technologies of PBF are selective laser melting (SLM), direct metal laser sintering (DMLS), and electron beam melting (EBM) (Duda and Raghavan, 2016). These technologies work based on laser scanning of metallic powders that are sintered and bonded together using high laser power. After each layer scanning, the powder bed is lowered down by one layer thickness, and a new layer is added on top by a roller. On the other hand, DED also uses high laser power to bond metal powders, but its powder adding system is different from PBF technologies. It has a deposition head where the powder is supplied, and a laser is mounted on it(Ali *et al.*, 2019).

When the scale of a printing object gets greater, 3D printing with metals suffers from limitations in terms of time and cost (Delgado Camacho *et al.*, 2018). Nevertheless, there are some 3D printing implemented projects. For instance, the Joris Laarman Lab and Arup developed the

MX3D technology, which uses a robot arm with gas metal arc welding (GMAW) to weld small stainless steel segments (Mrazovi et al., 2017). They designed and printed a 3D printed fully functional stainless steel 8 m footbridge with complex and unique geometries by using MX3D to cross one of the oldest canals in Amsterdam, the Oudezijdz Achterburgwal (see Fig. 1)

Figure 1. MX3D bridge (Liwanag, 2020).

Arup developed another example of using metal 3D printing for the design of tensegrity structures. The company studied different geometries and manufacturing processes for a structural net of cables in The Hague, the Netherlands, used for street lighting (Galjaard *et al.*, 2015b). Arup designed several structures using conventional and 3D printing techniques to show the possible savings obtained using topology optimization and 3D printing (Fig. 2). The estimation by Arup showed that topology optimization and the use of 3D printing are capable of decreasing the weight of a single node by 75% compared to the use of conventional methods. As a result, the estimated reduction was more than 40% of the weight of the whole structure (Galjaard *et al.*, 2015b).

Figure 2. Node models: traditional way (left), 3D printing method (right) (Galjaard *et al.*, 2015a).

Buchanan et al. (Buchanan *et al.*, 2017) investigated the behavior of 3D printed stub columns and coupons (for compression and tensile tests) from stainless steel PH1 and 316L. They used the powder bed fusion technique to print their test specimens. They showed that 3D printed metals could be used as structural elements in construction engineering in the future.

Khoshnevis and Zhang (2016) developed a new powder-based 3D printing called selective separation sintering (SSS), which can fabricate parts in ceramics and metals, which is much faster and relatively inexpensive than all other powder-based printers. In another study (Khoshnevis and Zhang, 2015), SSS was shown to be a suitable technique for large-scale fabrication due to its advantages over other techniques. Moreover, the method is feasible in the construction industry and aerospace construction on planetary surfaces.

All these material types for construction 3D printers allow AC to be applied in many civil engineering instances. Hence, the following section will present some application examples of AC.

3. Applications of 3D printing in construction

Several applications of 3D printing in civil engineering have been demonstrated successfully. The Eindhoven University of Technology designed a new type of 3D printer, which can print constructions with high accuracy in 2015 (Zhang *et al.*, 2019). In 2016 the first multi-story building was printed using the same method, and it has been already used as the Museum of the Future in Dubai (Starr, 2016). It was printed in Shanghai by WinSun Company in 17 days. The building was shipped to Dubai and assembled in two days (Gregerson, 2016). The cost of the building was approximately 140 000 USD, and the area was 242m^2. 3D printing reduced labor costs by 50-80% and reduced waste by 30-60% (Busta, 2016).

WinSun showed that AC could be implemented to the tall building constructions by building a 5-story building (Starr, 2015). The company also printed an 1100 m^2 villa (Fig. 3). The company stated that it had used ground construction and industrial waste around a base of quick-drying concrete mixed with a special hardening agent. The company is aiming to build large-scale structures in the future, such as bridges and skyscrapers.

Figure 3. 3D printed buildings by WinSun (Starr, 2015).

Some researchers argue that WinSun is not 3D printing their buildings since they use other construction methods during assembly in situ (Scott, 2016) (Fig. 4). It causes difficulties and requires more production areas and more labor for the construction than many other AC systems (Wang, 2015).

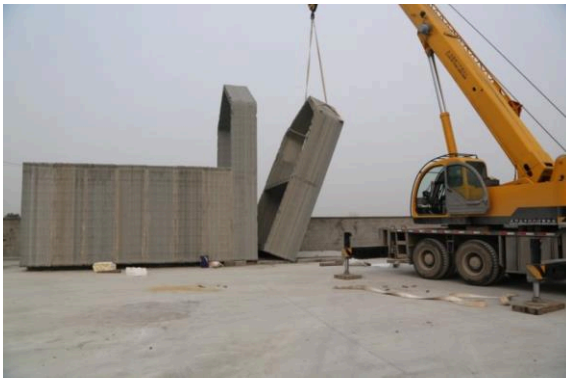

Figure 4. Assembly process of houses printed by WinSun (Deckert, 2015)

Hua Shang Tengda is another competitor construction company in China that built a 400 m^2 two-story house (Fig. 5) in one and a half months by AC (Scott, 2016). The building can withstand earthquakes with a magnitude of 8.0 (Stella, 2016).

Figure 5. 3D printed house by HuaShang Tengda

Russian engineers have also worked on AC. Similarly, APIS COR company has developed a mobile construction 3D printer (Fig. 6). APIS COR printer can build a construction structure from inside due to its unique design. It can remain in one spot and fabricate concrete walls layer-by-layer (Vatin *et al.*, 2017).

Figure 6. APIS COR 3D printer (Vatin *et al.*, 2017) and its application (Yin *et al.*, 2018)

APIS COR/PIK built a 38 m^2 home using their 3D printer in 2016 (Fig. 6). The system does not require any additional equipment setup as gantry-based printer systems do. The printing area is 132 m^2 with a fully rotating manipulating arm that can be extended from 4 to 8.5 m (Yin *et al.*, 2018). Even though many applications exist, additive construction is still in its infancy stage (Paul *et al.*, 2018).

Each AC application utilizes different building techniques. Generally, the AC building techniques can be grouped into contour crafting, concrete printing, D-shape printing, rock printing, and many others. A detailed description of these building techniques will be given below.

4. Building techniques

The widely known additive building methods are contour crafting (Khoshnevis *et al.*, 2006), concrete printing (Lu *et al.*, 2019), and D-shape printing (Zhang *et al.*, 2019). Some new techniques were also designed, such as selective binder activation

(SBA), selective paste intrusion (SPI), and rock printing (Lowke *et al.*, 2018). Initial AC prototypes of concrete printing worked with the same principles to FDM on a large scale with a deposition head system mounted on a gantry (Gibbons *et al.*, 2010). FDM-based AC uses the cheapest materials, among other AC systems (Holt *et al.*, 2019).

Additive construction is a special type of 3D printing used for construction on a larger scale than traditional 3D printing. The primary material of additive construction is concrete materials. Printing with concrete works with the same principles as inkjet printing, working with a pipe-pump-nozzle system.

4.1 Contour crafting

Contour Crafting (CC) is an additive manufacturing process that extrudes cement-based paste materials (Lim *et al.*, 2012). CC has higher surface quality than other AC types. CC is considered a pioneering project in AC that was proposed in 1998 by Khoshnevis et al. at the University of Southern California (Khoshnevis and Dutton, 1998). It uses a gantry enabling a 3D printer to move along Cartesian coordinate X, Y, and Z axes. In similar researches (Khoshnevis *et al.*, 2001, Khoshnevis, 2004), authors have developed an extrusion system for ceramic materials, such as spackling compounds and clay. The system consists of a piston, a cylinder that carries raw material, and a threaded feed rod that pushes the material through the nozzle. The technology's key feature is the high smoothness of printed surfaces obtained due to trowels mounted on the extrusion system (Hwang and Khoshnevis, 2005b). The resolution of the printer is around 13 mm. In another study, Khoshnevis et al., 2016 used sulfur concrete as the construction material and performed an experimental study to observe the contour crafting process based on the variation in (sulfur concrete and extruder) temperature, sulfur proportion, and extrusion rate. It was found that the sulfur proportion and temperature of the mix significantly influenced the extrudate surface. The experimental results were found in close agreement with the FEA analysis performed for comparison. Sulfur concrete is reported as an ideal construction material for planetary applications.

Zhang and Khoshnevis (Zhang and Khoshnevis, 2013) suggested a systematic method for planning and optimizing CC printing to build complicated large-scale buildings effectively. The authors have investigated the possibilities of constructing domes and developed them without using external supports or molds (Hwang and Khoshnevis, 2005a, Khoshnevis, 2004, Zhang and Khoshnevis, 2013, Zhang and Khoshnevis, 2009). For the CC process, the bonding strength between layers was studied by Zareiyan and Khoshnevis (2017). The impacts of cementitious material, water to cement ratio, fiber content quantity, and chemical admixture on interlayer adhesion were investigated. Significant variation in interlayer adhesion was observed which shows that it is important to select proper mixture ingredients for improved interlayer adhesion.

4.2 Concrete Printing

Since 2007, researchers from Loughborough University in the UK and a construction company called Skanska have collaborated to build a 3D concrete printing system with a robot arm and a gantry and facilitate AC's transition to the commercially feasible form of construction (Loughborough University, 2014). This is developing technology and therefore has limited inking materials available. At present, cementitious materials such as clay, Portland cement, special gypsum materials, dry mortar, and other dry materials like fly ash and sand are being used as an inking material for 3D concrete printing. Researchers are continuously putting efforts in determining the most appropriate inking materials along with their optimum proportion values for 3D concrete printing at both academic and industrial levels. Ding et al., 2018 prepared a cement-based material by incorporating hydroxypropyl methylcellulose (HPMC) into sulphoaluminate cement (SAC). A remarkable improvement in the compressive strength values was reported for the extruded mortar.

The printing process is called Freeform Construction, also known as Concrete Printing. It is also based on the extrusion system of the concrete; however, it has a smaller resolution and better control of geometries than the CC type of AC. It uses a second material to support the printing object, similar to the Fused Deposition Modelling (FDM) printing. However, it requires more maintenance and post-processing, such as removal of the support structure. The printer's resolution is 4 to 6 mm.

The material extrusion system is very similar to FDM or inkjet printing, which has a nozzle that extrudes heated materials on a predefined path that solidifies later. The extrusion system uses a pump to generate pressure inside the extruder and supply pipe (Fig. 7). The size of the aggregate particle is very important as a very large particle size may clog the nozzle. On the other hand, very small particle size can lead to an increase in the hydration heat of the cement. Therefore, selecting an appropriate aggregate particle size is important and depends on the size of the nozzle used.

Figure 7. Material extrusion system (Paolini *et al.*, 2019).

Another case study of a design and construction process for a self-supporting curvilinear multipurpose pavilion is presented (Lapyote et al., 2021). The case study methods included computer-aided design, structural analysis, joint assembly, and site construction techniques. The paper presented the current limitations and benefits of the existing technology for 3DP design and construction.

A polymer concrete-based large-scale printing for construction was studied and the influence of process parameters on the material was evaluated (Krčma et al., 2021). The mechanical properties of the longitudinal samples were close to the casting one. However, a difference was observed in the failure mode between the states, with casting parts showing a tougher behavior. Whereas, the 3D-printed samples exhibited high degrees of porosity. The results suggest that the novel material is suitable for 3D printing, with minor degradation observed in the process. It was found excellent layer adhesion with negligible effect on the finished part for the longitudinal orientation. It indicates, if the large-scale buildability is successful, the material is very suitable for 3D printed building components and other large-scale building structures (Krčma et al., 2021).

A recent work reveals nine potential factors and thirty-two of their measurements that determine the decision to adopt 3D printing technology for construction projects. A structural equation modeling technique was employed to quantify the influence of the relevant factors and measurements. The findings indicate the three most significant factors in ensuring the success of 3D printing technology in construction, namely; “technology compatibility,” “supply-side benefits,” and “complexity.” (Svetlana et al., 2021)

Another research presented the fabrication of specimens used to assess geometric and mechanical properties of the 3D printed parts. Two separate water-based binder formulations were used that are compatible with OPC chemistry and piezoelectric jetting. This study determines the effect of binder flow rate on dimensional accuracy. In addition, the changes in the mechanical properties over time with hydration have been explained (Ur-Rehman et al., 2021).

A similar study addressed the influence of concrete mixers in additive construction. The conventional concrete mixtures show that a high percentage of coarse aggregate is unsuitable for additive construction due to the effect of clogging the extruder. However, reducing the amount of coarse aggregate provides promising mixtures for additive construction. This work shows that a concrete mixture using conventional materials can be suitable for material extrusion in additive construction. The use of conventional materials will reduce costs and allow for additive construction to be used worldwide (Rushing et al., 2017).

4.3 D-Shape printing

D-shape printing is one of the well-known AC techniques that provide an alternative method for concrete printing, and the technology uses powder-based materials and binder jetting systems (Monolite UK (Dinitech SpA), 2016). It deposits selectively liquid adhesives on top of the cement powder layer. The cycle repeats until the whole object is printed. The spots of powder where the binder is applied, solidify creating high bonding between powder particles (Fig. 8). In the end, it is necessary to clean the powder support. The accuracy of the printer is 10 – 20 mm. There are two input materials needed to be supplied: a liquid binder and dry powder. Magnesium oxide and magnesium chloride are used as binder materials (Delgado Camacho *et al.*, 2018).

Figure 8. D-Shape printing technology (Monolite UK (Dinitech SpA), 2016).

A research team (Giovanni et al., 2014) employed D-shape printing and successfully developed full-scale building components using lunar soil. It is stated that D-shape printing will permit the military to develop infrastructures like bases, bunkers, and hospitals considerably faster compared to other traditional methods.

The main exceptional feature of the system is that it does not require printing support structures since the powder that is not glued performs as support to the printing structure

(Perkins and Skitmore, 2015). Another advantage of D-shape printing is that it has an extensive material selection range. It can use any sand-like materials, and there is no waste left after printing since leftovers can be reused for the next construction. In addition, the printed structures naturally look like stone due to fewer preprocessing materials at the beginning of the process (Tibaut *et al.*, 2016). On the other hand, powder printing brings difficulties with cleaning and printing in situ (Hussein, 2021).

4.4 Robots

Robot manipulators are another way of additive construction that can perform complex tasks on a large scale. They are designed to be stable at any point during operation. Batiprint3DTM company (Batiprint3D) developed eco-friendly mobile robot 3D printer systems that can reduce working conditions for labor, decrease environmental costs, and increase execution quality. They produce a layer of insulation on both sides of the concrete with polymer materials. However, the printed layers are not smooth, and the layers require protection from external effects.

Another robotic system called the ATHLETE platform was proposed by Howe *et al.* (2015), a six-limbed wheel-on-limb robotic platform capable of doing various tasks, including AC free from human hands. The authors believe that the proposed construction system can be useful in remote places and hazardous environments such as disaster areas, radiation, and war zones.

Gramazio Kohler collaborating with ETH Zurich University, carried out a project where flying drones assembled the first architectural installation without human intervention. The construction of a large-scale art was demonstrated at the FRAC in Orleans, France (Gramazio & Kohler and Raffaello D`Andrea in cooperation with ETH Zurich, 2011). The installation consisted of 1500 modules placed by drones programmed and moved with mathematical algorithms that converted digital data into drones' behaviors.

4.5 Accelerated chemical and mineral additives for extrusion control

Nozzle or extrusion control is the primary focus to achieve successful printing. In the extrusion process, additive chemicals and minerals play an important role.

Chemical additives are used in concrete designed for extrusion and buildability purposes. It was observed that the setting time of printing concrete can be controlled with chemical additives such as potassium carbonate (K2CO3), sodium carbonate (Na2CO3), calcium nitrate (Ca(NO3)2), and triethanolamine (TEA) (Dorn et al.). A comparison between nano-and micro-sized admixtures such as nano-silica, graphene-based materials, and clay nanoparticles and the chemical admixtures such as viscosity-modifying admixtures and superplasticizers are critically discussed (Sikora et al., 2021).

An organic foam-based 3D printing has its flammability and tendency to spread fires in buildings. Due to this, chemical additives such as flame retardant and smoke suppressive are added to the foam (Patric et al., 2021).

Using additives such as polycarboxylate plasticizers helps to regulate the mobility of cement systems at a constant W/C ratio. Additionally, it increases mechanical strength with the addition of active additives such as micro-silica, fly ash, and shell rock flour (Aleksandr et al, 2018). Some important additives such as; eco-friendly binders (silica fume, metakaolin, fly ashes), nanoparticles (nano-silica,nano-attapulgite clay), and chemical additives are very useful for tuning the rheology of concrete which controls the materials flow in a nozzle. (Rehman et al., 2021).

Some other important factors also influence the recent development of smart manufacturing technology. Among them, digital manufacturing plays an important role in determining product development costs. Before analyzing the product development cost, it is very risky to start building products. Another technological advancement namely the digital twin; helps to integrate digital data in real-time applications. Both have potential applications in construction engineering. The next section elaborates more on it.

5. Application of digital manufacturing (DM) and digital twin (DT) methods in AC

One example of digital manufacturing (DM) and digital twin (DT) in the construction industry is so-called building information modelling (BIM) (Kubicki *et al.*, 2019). BIM is a sophisticated type of management in building construction involving all the construction lifecycle stages from planning to post-construction facility management (Eastman *et al.*, 2011).

It includes crucial data such as geometric data, materials management, equipment utilization, resource and manufacturing data (Wu *et al.*, 2016). These data enable not only smoother collaboration between different teams but also the integration of automation techniques like 3D printing and robotics in construction. Moreover, a higher degree of automation of many planning procedures can be reached, owing to the interlinkage of these data (Borrmann *et al.*, 2015, Paolini *et al.*, 2018, Paolini *et al.*, 2019).

An AC process based on BIM can dramatically reduce the lead time, for instance through straightforward utilization of the design modifications in construction 3D printing (Ding *et al.*, 2019). In addition, the ability of BIM to store and arrange material delivery data, printer control data, and post finishing operations data can be applied to fully automate the AC process (Tay *et al.*, 2017, Teizer *et al.*, 2018).

Nowadays, DT and BIM terms are merged and can be used to refer to the same thing. Nevertheless, there is a difference. Specifically, BIM is mainly used to characterize static models while DT represents dynamic models of the building. Even though DT is being widely researched and found to be helpful in many industries, it is still less considered in the construction industry (Opoku *et al.*, 2021).

Khajavi *et al.* (2019) and Sacks *et al.* (2020) defined and described the current issues of DT application in the construction industry. To be specific, Khajavi *et al.* (2019) recognized that there is no possibility of using sensor networks for smart building development with the Internet of Things (IoT). In addition, Sacks *et al.* (2020) concluded that an agreement has not been reached between researchers about the particular benefits of DT in designing and constructing buildings.

Overall, 3D printing based on the BIM process can be beneficial in terms of cost and labor savings. However, the industry application is still in the infancy stage, and more research is required in order to bridge the gaps between 3D printing and BIM.

The construction of 3D printing has been developing rapidly with available expanding materials and different building techniques. However, there are a number of drawbacks to be overcome before the construction of

3D printing is used widely. The following section will present the current limitations of AC.

6. Limitations of AC

The main limitation is a narrow range of compatible materials that can be printed (Holt *et al.*, 2019). Besides, constructions and buildings are different products from other 3D printed products because they cannot be produced massively (Hodson, 2013). Moreover, the printing size is limited, and printed buildings have lower mechanical properties than traditional buildings (Holt *et al.*, 2019, Le *et al.*, 2012, Strauss, 2013, Feng *et al.*, 2015).

Feng *et al.* (2015) and Le *et al.* (2012) studied the mechanical properties of the 3D printed concrete elements. They found that voids and anisotropic material distribution led to poor load-bearing performances of the 3D printed concrete structures.

Reinforcements improve the mechanical properties and structural integrity of the 3D printed concrete structures. These can be achieved by a hybrid printing approach where concrete and reinforcement materials are printed simultaneously (Tay *et al.*, 2017, Sevenson, 2015). However, these kinds of reinforcements add more complexity and more cost to the printed final building.

One of the big issues of concrete 3D printing is the poor surface finish of the final product. If the construction is large and the build speed is preferable over the cost (i.e., emergency housing), then the poor surface finish can be unimportant. However, ridged textures of the consumer dwellings can be troublesome (Holt *et al.*, 2019). Generally, this poor surface quality of 3D concrete printing is attributed to several factors such as dimensional errors and improper control of deposited materials (deposited materials can be in excess or insufficient) (Panda *et al.*, 2018a).

Hence, the printing process needs to be properly controlled, and expensive surfaces after treatments must be applied if the surface quality is of concern (Hack and Kloft, 2020).

Moreover, the 3D-printed buildings or their elements do not comply with standardization regulations and building codes in the current situation. This is due to the novelty of the technique, and not all the utilized materials are standardized. Even though these novels and not standardized materials are to be used, it requires different maintenance approaches. In addition, the information about the long-term durability and longevity of the 3D printed civil engineering structures is not available as the oldest structures were built a few years ago. Overall, guidelines and standards must be formulated with profound investigations to construct 3D printing to become an accepted approach (Buchanan and Gardner, 2019).

Even though there are challenges of application of AC, this technique possesses the high potential of enhancing the current construction 3D printing by automating the process, which reduces construction defects by lowering human-induced errors. The future prospects of AC are discussed in the next section.

7. Future prospects of additive construction

As it was mentioned before, AC offers overwhelming advantages and various possibilities by reducing construction time. This technology is now aimed at solving global issues of providing cheap housing for low-income people, local reconstruction of houses after natural disasters such as earthquakes and floods, as well as military operations. AC also offers lower resource intensity of construction, including material consumption and labor costs and less environmental damage such as waste and noise pollution.

Moreover, AC can be handy in exploring space for human beings for two reasons. At first, the transportation of construction materials to the space is extremely high-priced. For instance, simply transporting an ordinary brick would require $2 million to the Moon (Leach, 2014). The next is the safety reasons. The automated construction systems would not require human presence by significantly decreasing risks on construction sites. NASA has a high level of interest in AC since they want to build different infrastructures on other planetary surfaces. NASA and the inventor of the CC printing system have collaborated to improve and develop the AC technology to implement other planetary surfaces in situ (Mars and Moon) (Krassenstein, 2015).

Additionally, according to Hossain et al. (2020) companies have been increasing the number of construction robots to solve the deficit of skilled labor and to increase efficiency, safety, and profit. It was projected that total revenue on construction 3D robots will grow up to USD 226 mln in 2025. According to Market Analysis Report (2021), the total market size increased from 7081.7 thousand USD in 2020 to 10943.9 thousand USD in 2021. It was expected that the total revenue of AC will grow at a rate of 91.5% every year till 2028 and reach USD 1034096.7 thousand. Becoming a useful and practical alternative for conventional construction and the widespread use of ACs are strongly related to the quality of the printed object and variety of advanced materials, which are structurally strong, highly fire-resistant, and low cost. Future works in additive manufacturing in architecture will continue in these directions. Other future research areas will involve printers' capability to build highly large-scale constructions and more advanced automation systems (Yin *et al.*, 2018).

8. Conclusions

To sum up, the application of 3D printing in construction engineering can be beneficial in automating building processes, time and material savings, complex shaped designs, elimination of worker's involvement in hazardous sites, and so on. Moreover, with technological advancement and novel material innovation, the application of AM in AC will become widespread in the near future. However, the extensive usage of AC is restricted due to some implementation facts, including the absence of a regulatory framework, narrow material selection range, the complexity of the systems, and limited applications. It will require continuous research and development in this field by the experts; such as engineers, architects, designers, and builders, to think and innovate new methods, mechanisms, and directions. Many research works are still needed to fully realize AC as an efficient and reliable option in the construction field. At present, not only research groups are involved in developing this system, but also large companies are investing in and developing these methods and mechanisms. The interest is apparent, and 3D printing might change the construction market dramatically. Finally, with the availability of material selection, the process parameter optimization, and application of IoT in terms of digital twin will add a new dimension towards flexible manufacturing in industrial automation.

References

Alhumayani, H., Gomaa, M., Soebarto, V. and Jabi, W. (2020), "Environmental assessment of large-scale 3D printing in construction: A comparative study between cob and concrete", *Journal of Cleaner Production,* Vol. 270, p. 122463.

Ali, M. H., Abilgaziyev, A. and Adair, D. (2019), "4D printing: a critical review of current developments, and future prospects", *The International Journal of Advanced Manufacturing Technology,* Vol. 105 No. 1, pp. 701-717.

Aleksandr Inozemtcev *et al* 2018 *IOP Conf. Ser.: Mater. Sci. Eng.* **365** 032009.

Annappa, V., Gaspar, F., Mateus, A. and Vitorino, J. (2021), "3D Printing for Construction Using Stone Sludge", *Sustainability and Automation in Smart Constructions*, Springer, pp. 121-130.

Batiprint3D "Batiprint3D", available at: https://www.batiprint3d.com/en (accessed 27 May 2021)

Biltcliffe, J. (2016), "Repurposing Portland Stone Waste with the Novi 3D Printer", available at: http://www.3ders.org/articles/20160527-repurposing-portland-stone-waste-with-the-novi-3d-printer.html (accessed 27 May 2021).

Biswas, K., Rose, J., Eikevik, L., Guerguis, M., Enquist, P., Lee, B., Love, L., Green, J. and Jackson, R. (2016), "Additive Manufacturing Integrated Energy—Enabling Innovative Solutions for Buildings of the Future", *Journal of Solar Energy Engineering,* Vol. 139 No. 1.

Borrmann, A., König, M., Koch, C. and Beetz, J. (2015), *Building Information Modeling: Technologische Grundlagen und industrielle Praxis,* Springer-Verlag.

Bos, F., Wolfs, R., Ahmed, Z. and Salet, T. (2016), "Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing", *Virtual and Physical Prototyping,* Vol. 11 No. 3, pp. 209-225.

Buchanan, C. and Gardner, L. (2019), "Metal 3D printing in construction: A review of methods, research, applications, opportunities and challenges", *Engineering Structures,* Vol. 180, pp. 332-348.

Buchanan, C., Matilainen, V.-P., Salminen, A. and Gardner, L. (2017), "Structural performance of additive manufactured metallic material and cross-sections", *Journal of Constructional Steel Research,* Vol. 136, pp. 35-48.

Busta, H. (2016), "Gensler Completes the World's First 3D-Printed Office Building", available at: https://www.architectmagazine.com/technology/gensler-designs-the-worlds-first-3d-printed-office-building-in-dubai_o (accessed 26 May 2021).

Deckert, T. (2015), "World's First 3D Apartment Complex Printed In China", available at: https://popupcity.net/observations/worlds-first-3d-apartment-complex-printed-in-china/ (accessed 27 May 2021)

Delgado Camacho, D., Clayton, P., O'Brien, W. J., Seepersad, C., Juenger, M., Ferron, R. and Salamone, S. (2018), "Applications of additive manufacturing in the construction industry – A forward-looking review", *Automation in Construction,* Vol. 89, pp. 110-119.

Ding, Z., Liu, S., Liao, L. and Zhang, L. (2019), "A digital construction framework integrating building information modeling and reverse engineering technologies for renovation projects", *Automation in Construction,* Vol. 102, pp. 45-58.

Dini, E. "D-Shape – The 21st century revolution in building technology has a name", available at: http://www.cadblog.pl/podcasty/luty_2012/d_shape_presentation.pdf (accessed 27 May 2021)

Doris (2016), "3D Concrete Printing Market to Reach $ 56.4 Million by 2021", available at: https://www.3printr.com/3d-concrete-printing-market-reach-56-4-million-2021-1239664/ (accessed 26 May 2021).

Dorn, T.; Hirsch, T.; Stephan, D. Study on the Influence of Accelerators on the Hydration of Portland Cement and Their Applicability in 3D Printing. In Rheology and Processing of Construction Materials; Springer: Berlin/Heidelberg, Germany, 2019; pp. 382–390.

Duballet, R., Baverel, O. and Dirrenberger, J. (2017), "Classification of building systems for concrete 3D printing", *Automation in Construction,* Vol. 83, pp. 247-258.

Duda, T. and Raghavan, L. V. (2016), "3D Metal Printing Technology", *IFAC-PapersOnLine,* Vol. 49 No. 29, pp. 103-110.

Eastman, C. M., Eastman, C., Teicholz, P., Sacks, R. and Liston, K. (2011), *BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors,* John Wiley & Sons.

Feng, P., Meng, X., Chen, J.-F. and Ye, L. (2015), "Mechanical properties of structures 3D printed with cementitious powders", *Construction and Building Materials,* Vol. 93, pp. 486-497.

Furet, B., Poullain, P. and Garnier, S. (2019), "3D printing for construction based on a complex wall of polymer-foam and concrete", *Additive Manufacturing,* Vol. 28, pp. 58-64.

Galjaard, S., Hofman, S., Perry, N. and Ren, S. (2015a), "Optimizing structural building elements in metal by using additive manufacturing", in *Proceedings of IASS Annual Symposia*, Vol. 2015, pp. 1-12.

Galjaard, S., Hofman, S. and Ren, S. (2015b), "New Opportunities to Optimize Structural Designs in Metal by Using Additive Manufacturing", in Cham, pp. 79-93.

Geneidy, O., Ismaeel, W. S. E. and Abbas, A. (2019), "A critical review for applying three-dimensional concrete wall printing technology in Egypt", *Architectural Science Review,* Vol. 62 No. 5, pp. 438-452.

Gibbons, G. J., Williams, R., Purnell, P. and Farahi, E. (2010), "3D Printing of cement composites", *Advances in Applied Ceramics,* Vol. 109 No. 5, pp. 287-290.

Giovanni Cesaretti, Enrico Dini, Xavier De Kestelier, Valentina Colla, Laurent Pambaguian, Building components for an outpost on the Lunar soil by means of a novel 3D printing technology, Acta Astronautica, Volume 93,2014, Pages 430-450, ISSN 0094-5765,https://doi.org/10.1016/j.actaastro.2013.07.034.

Gramazio & Kohler and Raffaello D`Andrea in cooperation with ETH Zurich (2011), "Flight Assembled Architecture, 2011-2012", available at: http://www.gramaziokohler.com/web/e/projekte/209.html (accessed 27 May 2021)

Gregerson, J. (2016), "Inside the Very First 3D-Printed Office Building", available at: https://builtworlds.com/news/inside-first-3d-printed-office-building/ (accessed 27 May 2021).

Hack, N. and Kloft, H. (2020), "Shotcrete 3D Printing Technology for the Fabrication of Slender Fully Reinforced Freeform Concrete Elements with High Surface Quality: A Real-Scale Demonstrator", in *RILEM International Conference on Concrete and Digital Fabrication*, pp. 1128-1137.

Hager, I., Golonka, A. and Putanowicz, R. (2016), "3D Printing of Buildings and Building Components as the Future of Sustainable Construction?", *Procedia Engineering,* Vol. 151, pp. 292-299.

Hambach, M., Rutzen, M. and Volkmer, D. (2019), "Chapter 5 - Properties of 3D-Printed Fiber-Reinforced Portland Cement Paste", in Sanjayan, J. G., Nazari, A. and Nematollahi, B. (Eds.) *3D Concrete Printing Technology*, Butterworth-Heinemann, pp. 73-113.

Hodson, H. (2013), "Robo-builders deliver architects' dreams", *New scientist,* No. 2913, pp. 22-23.

Holt, C., Edwards, L., Keyte, L., Moghaddam, F. and Townsend, B. (2019), "Chapter 17 - Construction 3D Printing", in Sanjayan, J. G., Nazari, A. and Nematollahi, B. (Eds.) *3D Concrete Printing Technology*, Butterworth-Heinemann, pp. 349-370.

Hossain, M. A., Zhumabekova, A., Paul, S. C., & Kim, J. R. (2020). A review of 3D printing in construction and its impact on the labor market. Sustainability, 12(20), 8492.

Howe, A. S., Wilcox, B., McQuin, C., Mittman, D., Townsend, J., Polit-Casillas, R. and Litwin, T. (2015), "Modular Additive Construction Using Native Materials", *Earth and Space 2014*, pp. 301-312.

Hussein, A. (2021). Review Paper on 3D Printing Concrete Technology and mechanics from industrial aspect. International Journal of Engineering Applied Sciences and Technology, 5(12).

Hwang, D. and Khoshnevis, B. (2005a), "An Innovative Construction Process-Contour Crafting (CC)", in.

Hwang, D. and Khoshnevis, B. (2005b), "An innovative construction process-contour crafting (CC)", in *22nd International Symposium on Automation and Robotics in Construction*, Vol. 90111.

Ibrahim, M. I. M. (2016), "Estimating the sustainability returns of recycling construction waste from building projects", *Sustainable Cities and Society,* Vol. 23, pp. 78-93.

Jandyal, A., Chaturvedi, I., Wazir, I., Raina, A., & Ul Haq, M. I. (2022). 3D printing – a review of processes, materials and applications in industry 4.0. Sustainable Operations and Computers, 3, 33–42.

Joosten, S. (2015), "Printing a stainless steel bridge: An exploration of structural properties of stainless steel additive manufactures for civil engineering purposes".

Kazemian, A., Yuan, X., Cochran, E. and Khoshnevis, B. (2017), "Cementitious materials for construction-scale 3D printing: Laboratory testing of fresh printing mixture", *Construction and Building Materials,* Vol. 145, pp. 639-647.

Khajavi, S. H., Motlagh, N. H., Jaribion, A., Werner, L. C. and Holmström, J. (2019), "Digital Twin: Vision, Benefits, Boundaries, and Creation for Buildings", *IEEE Access,* Vol. 7, pp. 147406-147419.

Khoshnevis, B. (2004), "Automated construction by contour crafting—related robotics and information technologies", *Automation in Construction,* Vol. 13 No. 1, pp. 5-19.

Khoshnevis, B. and Dutton, R. (1998), "Innovative Rapid Prototyping Process Makes Large Sized, Smooth Surfaced Complex Shapes in a Wide Variety of Materials", *Materials Technology,* Vol. 13 No. 2, pp. 53-56.

Khoshnevis, B., Hwang, D., Yao, K.-T. and Yeh, Z. (2006), "Mega-scale fabrication by contour crafting", *International Journal of Industrial and Systems Engineering,* Vol. 1 No. 3, pp. 301-320.

Khoshnevis, B., Russell, R., Hongkyu, K. and Bukkapatnam, S. (2001), "Crafting large prototypes", *IEEE Robotics & Automation Magazine,* Vol. 8 No. 3, pp. 33-42.

Khoshnevis, B. and Zhang, J. (2015), "Selective Separation Sintering (SSS)-An Additive Manufacturing Approach for Fabrication of Ceramic and Metallic Parts with Application in Planetary Construction", in *AIAA SPACE 2015 Conference and Exposition*, p. 4450.

Khoshnevis, B. and Zhang, J. (2016), "Selective Separation Sintering for Metallic Part Fabrication", *Solid Freeform Fabrication 2016: Proceedings of the 26th Annual International*.

Krčma, M., Škaroupka, D., Vosynek, P., Zikmund, T., Kaiser, J. and Palousek, D. (2021), "Use of polymer concrete for large-scale 3D printing", *Rapid Prototyping Journal*, Vol. 27 No. 3, pp. 465-474. https://doi.org/10.1108/RPJ-12-2019-0316.

Kothman, I. and Faber, N. (2016), "How 3D printing technology changes the rules of the game", *Journal of Manufacturing Technology Management,* Vol. 27 No. 7, pp. 932-943.

Krassenstein, B. (2015), "Contour Crafting Inventor Dr. Khoshnevis: Widespread 3D Printed Homes in 5 Years, High-Rises in 10 Years", available at: https://3dprint.com/53437/contour-crafting-dr-khoshnevis/ (accessed 27 May 2021)

Kubicki, S., Guerriero, A., Schwartz, L., Daher, E. and Idris, B. (2019), "Assessment of synchronous interactive devices for BIM project coordination: Prospective ergonomics approach", *Automation in Construction,* Vol. 101, pp. 160-178.

Labonnote, N., Rønnquist, A., Manum, B. and Rüther, P. (2016), "Additive construction: State-of-the-art, challenges and opportunities", *Automation in Construction,* Vol. 72, pp. 347-366.

Lawson, N., Douglas, I., Garvin, S., McGrath, C., Manning, D. and Vetterlein, J. (2001), "Recycling construction and demolition wastes – a UK perspective", *Environmental Management and Health,* Vol. 12 No. 2, pp. 146-157.

Lapyote Prasittisopin, Ph.D.; Thanut Sakdanaraseth; and Vimolsiddhi Horayangkura," Design and Construction Method of a 3D Concrete Printing Self-Supporting Curvilinear Pavilion", Journal of Architectural Engineering, Volume 27 Issue 3 - September 2021.

Le, H. D., Kadri, E. H., Aggoun, S., Vierendeels, J., Troch, P. and De Schutter, G. (2015), "Effect of lubrication layer on velocity profile of concrete in a pumping pipe", *Materials and Structures,* Vol. 48 No. 12, pp. 3991-4003.

Le, T. T., Austin, S. A., Lim, S., Buswell, R. A., Gibb, A. G. F. and Thorpe, T. (2012), "Mix design and fresh properties for high-performance printing concrete", *Materials and Structures,* Vol. 45 No. 8, pp. 1221-1232.

Leach, N. (2014), *Space architecture: The new frontier for design research,* John Wiley & Sons.

Lim, S., Buswell, R. A., Le, T. T., Austin, S. A., Gibb, A. G. F. and Thorpe, T. (2012), "Developments in construction-scale additive manufacturing processes", *Automation in Construction,* Vol. 21, pp. 262-268.

Liwanag, V. (2020), "World's First 3D-Printed Metal Bridge", available at: http://emag.archiexpo.com/worlds-first-3d-printed-metal-bridge/ (accessed 27 May 2021)

Lloret, E., Shahab, A. R., Linus, M., Flatt, R. J., Gramazio, F., Kohler, M. and Langenberg, S. (2015), "Complex concrete structures: merging existing casting techniques with digital fabrication", *Computer-Aided Design,* Vol. 60, pp. 40-49.

Loughborough University (2014), "Partnership aims to develop 3D concrete printing in construction", available at: https://www.lboro.ac.uk/news-events/news/2014/november/204-skanska.html (accessed 27 May 2021)

Lowke, D., Dini, E., Perrot, A., Weger, D., Gehlen, C. and Dillenburger, B. (2018), "Particle-bed 3D printing in concrete construction – Possibilities and challenges", *Cement and Concrete Research,* Vol. 112, pp. 50-65.

Lu, B., Weng, Y., Li, M., Qian, Y., Leong, K. F., Tan, M. J. and Qian, S. (2019), "A systematical review of 3D printable cementitious materials", *Construction and Building Materials,* Vol. 207, pp. 477-490.

Market Analysis Report. 3D printing construction market size report, 2021-2028. 3D Printing Construction Market Size Report, 2021-2028. (2021). available at: https://www.grandviewresearch.com/industry-analysis/3d-printing-constructions-market. (accessed 26 October 2021)

Monolite UK (Dinitech SpA) (2016), "D-SHAPE", available at: http://3dprintetbyggeri.dk/pdf/besøgsrapporter/D-Shape.pdf (accessed 27 May 2021)

Mrazovi , N., Mocibob, D., Lepech, M. and Fischer, M. (2017), "Assessment of additive and conventional manufacturing: Case studies from the AEC industry.", in *Proceedings of International Structural Engineering and Construction*.

MX3D "MX3D", available at: https://mx3d.com (accessed 27 May 2021)

Opoku, D.-G. J., Perera, S., Osei-Kyei, R. and Rashidi, M. (2021), "Digital twin application in the construction industry: A literature review", *Journal of Building Engineering,* Vol. 40, p. 102726.

Panda, B., Chandra Paul, S., and Jen Tan, M. (2017a), "Anisotropic mechanical performance of 3D printed fiber reinforced sustainable construction material", *Materials Letters,* Vol. 209, pp. 146-149.

Panda, B., Tay, Y. W. D., Paul, S. C. and Tan, M. J. (2018a), "Current challenges and future potential of 3D concrete printing", *Materialwissenschaft und Werkstofftechnik,* Vol. 49 No. 5, pp. 666-673.

Panda, B., Unluer, C. and Tan, M. J. (2018b), "Investigation of the rheology and strength of geopolymer mixtures for extrusion-based 3D printing", *Cement and Concrete Composites,* Vol. 94, pp. 307-314.

Paolini, A., Frischmann, F., Kollmannsberger, S., Rabold, A., Horger, T., Wohlmuth, B. and Rank, E. (2018), "BIM gestützte strukturdynamische Analyse mit Volumenelementen höherer Ordnung/BIM-based structural dynamic analysis using higher-order volumetric finite elements", *Bauingenieur,* Vol. 93 No. 04, pp. 160-166.

Paolini, A., Kollmannsberger, S. and Rank, E. (2019), "Additive manufacturing in construction: A review on processes, applications, and digital planning methods", *Additive Manufacturing,* Vol. 30, p. 100894.

Patrick Bedarf, Alessandro Dutto, Michele Zanini, Benjamin Dillenburger, Foam 3D printing for construction: A review of applications, materials, and processes, Automation in Construction, Volume 130,2021,103861, ISSN 0926-5805,https://doi.org/10.1016/j.autcon.2021.103861.

Paul, S. C., van Zijl, G. P. A. G., Tan, M. J. and Gibson, I. (2018), "A review of 3D concrete printing systems and materials properties: current status and future research prospects", *Rapid Prototyping Journal,* Vol. 24 No. 4, pp. 784-798.

Pegna, J. (1997), "Exploratory investigation of solid freeform construction", *Automation in construction,* Vol. 5 No. 5, pp. 427-437.

Perkins, I. and Skitmore, M. (2015), "Three-dimensional printing in the construction industry: A review", *International Journal of Construction Management,* Vol. 15 No. 1, pp. 1-9.

Perrot, A., Rangeard, D. and Pierre, A. (2016), "Structural built-up of cement-based materials used for 3D-printing extrusion techniques", *Materials and Structures,* Vol. 49 No. 4, pp. 1213-1220.Rajgor,

M. B. and Pitroda, J. (2013), "A study of utilization aspect of stone waste in indian context", *International journal of global research analysis,* Vol. 2 No. 1.

Rehman, A.U.; Kim, J.-H. 3D Concrete Printing: A Systematic Review of Rheology, Mix Designs, Mechanical, Microstructural, and Durability Characteristics.*Materials* **2021**, *14*, 3800. https://doi.org/10.3390/ma14143800

Rubio, M., Sonebi, M. and Amziane, S. (2017), "3D printing of fibre cement-based materials: fresh and rheological performances", *Academic Journal of Civil Engineering,* Vol. 35 No. 2, pp. 480-488.

Rushing, T.S., Al-Chaar, G., Eick, B.A., Burroughs, J., Shannon, J., Barna, L. and Case, M. (2017), "Investigation of concrete mixtures for additive construction", *Rapid Prototyping Journal*, Vol. 23 No. 1, pp. 74-80. https://doi.org/10.1108/RPJ-09-2015-0124

Sacks, R., Brilakis, I., Pikas, E., Xie, H. S. and Girolami, M. (2020), "Construction with digital twin information systems", *Data-Centric Engineering,* Vol. 1, p. e14.

Sakin, M. and Kiroglu, Y. C. (2017), "3D Printing of Buildings: Construction of the Sustainable Houses of the Future by BIM", *Energy Procedia,* Vol. 134, pp. 702-711.

Scott, C. (2016), "Chinese Construction Company 3D Prints an Entire Two-Story House On-Site in 45 Days", available at: https://3dprint.com/138664/huashang-tengda-3d-print-house/ (accessed 27 May 2021)

Sevenson, B. (2015), "Shanghai-based WinSun 3D Prints 6-Story Apartment Building and an Incredible Home", available at: https://3dprint.com/38144/3d-printed-apartment-building/ (accessed 27 May 2021)

Shakor, P., Nejadi, S., Paul, G. and Malek, S. (2019), "Review of Emerging Additive Manufacturing Technologies in 3D Printing of Cementitious Materials in the Construction Industry", *Frontiers in Built Environment,* Vol. 4 No. 85.

Shakor, P., Nejadi, S., Sutjipto, S., Paul, G. and Gowripalan, N. (2020), "Effects of deposition velocity in the presence/absence of E6-glass fibre on extrusion-based 3D printed mortar", *Additive Manufacturing,* Vol. 32, p. 101069.

Sikora, P., Chougan, M., Cuevas, K. *et al.* The effects of nano- and micro-sized additives on 3D printable cementitious and alkali-activated composites: a review. *Appl Nanosci* (2021). https://doi.org/10.1007/s13204-021-01738-2

Soltan, D. G. and Li, V. C. (2018), "A self-reinforced cementitious composite for building-scale 3D printing", *Cement and Concrete Composites,* Vol. 90, pp. 1-13.

Starr, M. (2015), "World's first 3D-printed apartment building constructed in China", available at: https://www.cnet.com/news/worlds-first-3d-printed-apartment-building-constructed-in-china/ (accessed 27 May 2021)

Starr, M. (2016), "Dubai unveils world's first 3D-printed office building", available at: https://www.cnet.com/news/dubai-unveils-worlds-first-3d-printed-office-building/ (accessed 27 May 2021)

Stella, R. (2016), "It's hideous, but this 3D-printed villa in China can withstand a major quake", available at: https://www.digitaltrends.com/home/3d-printed-chinese-villas-huashang-tenda/ (accessed 27 May 2021)

Stone-ideas (2017), "3D-Printing with stone slurry: „Stone on Demand“ offers many new possibilities for the marble branch", available at: https://www.stone-ideas.com/55453/3d-printing-with-stone-slurry-stone-on-demand-offers-many-new-possibilities-for-the-marble-branch/ (accessed 27 May 2021)

Strauss, H. (2013), *Am envelope: the potential of additive manufacturing for facade constructions,* TU Delft.

Svetlana Besklubova; Miroslaw J. Skibniewski, M.ASCE; and Xueqing Zhang, " Factors Affecting 3D Printing Technology Adaptation in Construction", Journal of Construction Engineering and Management Volume 147 Issue 5 - May 2021.

Tay, Y. W. D., Panda, B., Paul, S. C., Noor Mohamed, N. A., Tan, M. J. and Leong, K. F. (2017), "3D printing trends in building and construction industry: a review", *Virtual and Physical Prototyping,* Vol. 12 No. 3, pp. 261-276.

Taylor, M., Wamuziri, S. and Smith, I. (2003), "Automated construction in Japan", in *Proceedings of the Institution of Civil Engineers-Civil Engineering*, Vol. 156, pp. 34-41.

Teizer, J., Blickle, A., King, T., Leitzbach, O., Guenther, D., Mattern, H. and König, M. (2018), "BIM for 3D Printing in Construction", in Borrmann, A., König, M., Koch, C. and Beetz, J. (Eds.) *Building Information Modeling: Technology Foundations and Industry Practice*, Springer International Publishing, Cham, pp. 421-446.

Tibaut, A., Rebolj, D. and Perc, M. N. (2016), "Interoperability requirements for automated manufacturing systems in construction", *Journal of intelligent manufacturing,* Vol. 27 No. 1, pp. 251-262.

Ur Rehman, A., and Sglavo, V.M. (2021), "3D printing of Portland cement-containing bodies", *Rapid Prototyping Journal*, Vol. ahead-of-print No. ahead-of-print. https://doi.org/10.1108/RPJ-08-2020-0195

Vaezi, M. and Chua, C. K. (2011), "Effects of layer thickness and binder saturation level parameters on 3D printing process", *The International Journal of Advanced Manufacturing Technology,* Vol. 53 No. 1, pp. 275-284.

Vahabi, H., Laoutid, F., Mehrpouya, M., Saeb, M. R., & Dubois, P. (2021). Flame retardant polymer materials: An update and the future for 3D printing developments. Materials Science and Engineering: R: Reports, 144, 100604.

Vatin, N. I., Chumadova, L. I., Goncharov, I. S., Zykova, V. V., Karpenya, A. N., Kim, A. A. and Finashenkov, E. A. (2017), "3D printing in construction", *Stroitel'stvo Unikal'nyh Zdanij i Sooruzenij,* No. 1, pp. 27-46.

Wang, B. (2015), "WinSun 3D printed sections of building then assembled them into a 5 story apartment", available at: https://www.nextbigfuture.com/2015/01/winsun-3d-printed-sections-of-building.html (accessed 27 May 2021)

Wu, P., Wang, J. and Wang, X. (2016), "A critical review of the use of 3-D printing in the construction industry", *Automation in Construction,* Vol. 68, pp. 21-31.

Xia, M. and Sanjayan, J. (2016), "Method of formulating geopolymer for 3D printing for construction applications", *Materials & Design,* Vol. 110, pp. 382-390.

Yin, H., Qu, M., Zhang, H. and Lim, Y. (2018), "3D Printing and Buildings: A Technology Review and Future Outlook", *Technology|Architecture + Design,* Vol. 2 No. 1, pp. 94-111.

Zhang, J. and Khoshnevis, B. (2009), *Contour crafting process planning and optimization,* University of Southern California.

Zhang, J. and Khoshnevis, B. (2013), "Optimal machine operation planning for construction by Contour Crafting", *Automation in Construction,* Vol. 29, pp. 50-67.

Zhang, J., Wang, J., Dong, S., Yu, X. and Han, B. (2019), "A review of the current progress and application of 3D printed concrete", *Composites Part A: Applied Science and Manufacturing,* Vol. 125, p. 105533.

Zhu, Z., Park, M.-W., Koch, C., Soltani, M., Hammad, A. and Davari, K. (2016), "Predicting movements of onsite workers and mobile equipment for enhancing construction site safety", *Automation in Construction,* Vol. 68, pp. 95-101.

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