Constraints and limitations of concrete 3D printing in architecture

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Abstract

Purpose – Additive manufacturing of concrete (AMoC) is an emerging technology for constructing buildings. However, due to the nature of the concrete property and constructing buildings in layers, constraints and limitations are encountered while applying AMoC in architecture. This paper aims to analyze the constraints and limitations that may be encountered while using AMoC in architecture.

Design/methodology/approach – A descriptive research approach is used to conduct this study. First, basic notions of AMoC are introduced. Then, challenges of AMoC, including hardware, material property, control and design, are addressed. Finally, strategies that may be used to overcome the challenges are discussed.

Findings – Factors influencing the success of AMoC include hardware, material, control methods, manufacturing process and design. Considering these issues in the early design phase is crucial to achieving a successful computer-aided design (CAD)/computer-aided manufacturing (CAM) integration to bring CAD and CAM benefits into the architecture industry.

Originality/value – In three-dimensional (3D) printing, objects are constructed layer by layer. Printing results are thus affected by the additive method (such as toolpath) and material properties (such as tensile strength and slump). Although previous studies attempt to improve AMoC, most of them focus on the manufacturing process. However, a successful application of AMoC in architecture needs to consider the possible constraints and limitations of concrete 3D printing. So far, research on the potential challenges of applying AMoC in architecture from a building lifecycle perspective is still limited. The study results of this study could be used to improve design and construction while applying AMoC in architecture.

Keywords Architecture, 3D printing, Additive manufacturing, Concrete

Paper type Literature review

1. Introduction

The architecture industry is often regarded as a traditional industry. One reason is that constructional operations are mostly performed by labor, such as bending steel, machining and nailing formwork and pouring concrete (Ko and Kuo, 2019). Construction costs mainly consist of materials and labor. In residential building projects, labor cost occupies approximately 25% to 35% and materials take the rest of the project costs (Gichuhi, 2019). Given that an architecture project's profit is about 10% to 20% of the total cost, the labor-intensive nature of the architecture industry renders the reduction of the construction cost difficult, thus reducing the margin of profit (Doloi, 2012).

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Occupational Safety and Health Act (OSHA) classifies construction work as one of the most dangerous occupations (Ministry of Labor, 2019; OSHA). Some workplaces are situated in height; others may require workers working underground. For high-rise building projects, workers need to operate in a windy situation, whereas for tunnel and sewer projects, they need to operate underground for hours. Common casualties in architecture projects include electrocutions, falls, being struck by an object or caught in one, slipping and tripping (Seo and Choi, 2008; Bock, 2004). While labor accidents may cause project delays, compensation and medical expenses increase the project's cost.

Construction automation has been considered a promising direction to overcome the labor-intensive and high-risk operational challenges faced in the architecture industry (Arashpour *et al.*, 2018; Lim *et al.*, 2011). In addition, concrete is a popular material that is inexpensive, durable, strong and accessible. Additive manufacturing of concrete (AMoC) thus has become one of the significant research realms in construction automation (Craveiroa *et al.*, 2019; Rael and Fratello, 2018; Perrot, 2019; Buswell, *et al.*, 2018).

Malaeb *et al.* (2015) broach the design of a concrete three-dimensional (3D) printer and material mix. The printing machine is designed for building a 77 cm × 10 cm structural wall. In contrast, the material mix focuses on experimenting with the optimal concrete formula, including aggregates, cement type, sand, superplasticizer, accelerator and a retarder, on performing the desired concrete functions. On the other hand, Nerella and Mechtcherine (2019) experiment with concrete printability, which is crucial for concrete 3D printing. In their study, four aspects are considered while selecting concrete raw materials: setting and hydration times, strength of hardened concrete, pumpability and workability and strength at a very early stage of concrete setting. In addition to Nerella and Mechtcherine (Nerella and Mechtcherine, 2019), some researchers, e.g. Le *et al.* (2012a, 2012b), Panda *et al.* (2018) and Ma *et al.* (2018) endeavor on improving concrete filament performance, such as extrudability, flowability and buildability. Still, other scholars attempt to improve AMoC using the ideas of "design by test" (Salet *et al.*, 2018) and toolpath planning (Gosselin *et al.*, 2016).

In 3D printing, objects are constructed layer by layer. Printing results are thus affected by the additive method (such as toolpath) and material properties (such as tensile strength and slump). Although many studies attempt to improve AMoC, most of them focus on the manufacturing process. However, a successful application of AMoC in architecture needs to consider the possible constraints and limitations of concrete 3D printing. So far, research on the potential challenges of applying AMoC in architecture from a building lifecycle perspective is still limited.

Architecture could be defined as the art and practice of designing and constructing buildings. This research aims to analyze the constraints and limitations that may need to be considered while using concrete 3D printing technology in buildings. Explanation and examples are thus encompassed around buildings and building components. A descriptive research approach is adopted to conduct the study. AMoC is first introduced, followed by the challenges it may encounter. Strategies used to overcome the challenges are discussed. Finally, research findings and future research directions are documented.

2. Additive manufacturing of concrete

Additive Manufacturing (AM) is a manufacturing process of building objects in layers (Gibson *et al.*, 2015). From this definition, AMoC could be defined as an AM process using concrete material (Bos *et al.*, 2016). AM could be categorized into seven types of processes (Guo and Leu, 2013; ISO/ASTM, 2015): binder jetting selectively deposits liquid binder agent to join powder materials; directed energy deposition uses thermal energy to fuse the materials as they are being deposited to form the object; in material jetting, droplets of the material are selectively deposited to form the object; material extrusion process selectively dispenses the material through a nozzle to deposit the object; for powder bed fusion, the thermal energy selectively fuses the regions of the powder bed to form the object; sheet lamination selectively cuts the sheets and bonds them to form the object; and finally, an object can be formed by selectively curing liquid photopolymer using light-activated polymerization. Concrete is made of a mixture of fine and coarse aggregates, cement and water by a certain ratio. It produces strength through hydration after a period of time. Due to the widespread use of concrete in architecture, material extrusion is a commonly used manufacturing process in AMoC (Perrot, 2016; Duballet *et al.*, 2017).

The early development of AMoC could be traced back to 1998, namely, the contour crafting technique, as shown in Figure 1(a).[28–31] The process involves inputting data to a gantry robot, followed by the material extrusion process. Binder-jetting, an AM process in which the liquid binder agent is selectively deposited to join powder materials, as shown in Figure 1(b), is another popular method used in large-scale AMoC (Cesaretti *et al.*, 2014; Lowke *et al.*, 2018). As the contour crafting technique can provide structural strength for printed objects, it has been widely used by far for constructing residential buildings (Tay *et al.*, 2017). In architecture, using AMoC to build a house can save the formwork required for traditional concrete operations and therefore reduce the labor and construction costs. In addition, the 3D printing robot can work much longer than a human can, greatly reducing the construction duration. Due to robotic construction, labor safety issues can also be significantly reduced. Furthermore, AMoC can reduce the use of materials, reduce construction waste and carbon emission and make the built environment more environmentally friendly (Bos *et al.*, 2016; Tay *et al.*, 2017). However, this technology is not yet mature; challenges and limitations are discussed in the subsequent sections.

3. Challenges of additive manufacturing of concrete

Among AM methodologies, material extrusion is the most popular one used in AMoC. As a result, this research focuses on addressing the challenges of the method. Due to the nature of the material extrusion depositing concrete filament layer by layer, challenges faced in AMoC

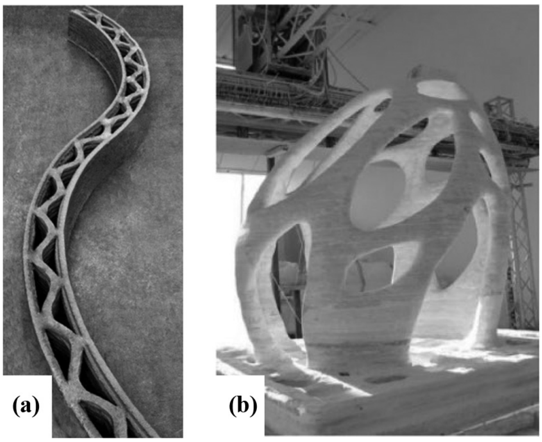

Figure 1. Additive manufacturing processes of concrete 3D printing: (a) counter crafting of material extrusion (Khoshnevis, 1998, 2004; Khoshnevis *et al.*, 2001, 2006) (reprinted with permission, STRUCTURE, September 2020) and (b) D-Shape of binder-jetting (Cesaretti *et al.*, 2014; Lowke *et al.*, 2018) (reuse with permission)

are categorized into five types: hardware, material property, software/control, manufacturing process and design. Details of each challenge are explained as follows.

3.1 Hardware

3.1.1 Dimension of the machine. The larger the printer size, the bigger the object can be printed. On the other hand, a large 3D printer with a single nozzle may take a long time to manufacture an object. The size of the printer and the printing time are a dilemma. The dimension for a large-scale concrete 3D printer ranges from 150 m × 10 m × 6.6 m, a gantry robot, to 3.7 m × 3.7 m × 2.8 m, for the selective compliance assembly robot arm (SCARA).

The minimum space for physical habitation for a human cannot be smaller than 4 m^2 (Baltic Human Rights Society, 2020). The height of the space should allow one door to be installed. Such a minimum habitational dimension is 2 m × 2 m × 2 m. Therefore, in architecture, the so-called large-size concrete 3D printer may imply that the printer can construct an object whose minimum dimensions are 2 m × 2 m × 2 m. In this definition of the large-scale concrete 3D printers, portability, transportation and storage could be challenging issues.

3.1.2 Mechanical motion. To deposit material on the designated location, the nozzle is moved by a mechanical mechanism. According to mechanical motion, six kinds of robots could be used in AMoC. The articulated robot features rotary joints, as shown in Figure 2(a) (Hsiao *et al.*, 2018); Cartesian robots, also known as gantry robots, have three linear joints that use the Cartesian coordinate system (X, Y and Z); the cylindrical robot has one rotary joint at the base and one prismatic joint at the top; Figure 2(b) demonstrates a polar robot, which is also called a spherical robot (CONSTRUCTIONS-3D. MAXI PRINTER, 2020); the SCARA robot shown in Figure 2(c) has two parallel joints moveable in the compliance plane (3D Potter, 2020a, 2020b); finally, a delta robot, features three arms connected to universal joints at the base (Wang, 2016).

Due to the difference in mechanical motion, each type of robotic system may be appropriate for different kinds of situations. The advantages and limitations of applying different types of robots in AMoC are summarized in Table 1. As shown in Figure 2(a), the articulated robot could provide highly accurate concrete printing for intricate design and a high degree of

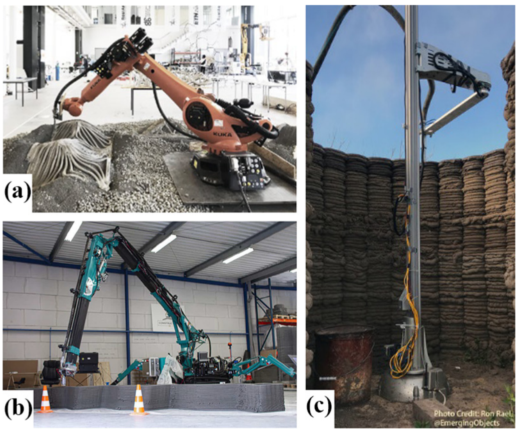

Figure 2. Robotic systems of 3D concrete printing. (a) Articulated robot (Hsiao *et al.*, 2018) (reuse with permission). (b) Polar robot (CONSTRUCTIONS-3D. MAXI PRINTER, 2020; https://en.constructions-3d.com/) (reuse with permission from Aniwaa Pte Ltd) (c) SCARA robot (3D Potter, 2020a, 2020b) (reuse with permission)

Table 1. Advantages and limitations of large-scale concrete 3D printing robotic systems

Motion	Degree of freedom	Advantages	Limitations
Articulated	6	– High mechanical precision – High degree of freedom suitable for printing intricate buildings	– Expensive – Limited workspace – Nozzle cannot reach the center of the work area
Cartesian	3	– Suitable for printing large-scale buildings – Suitable for printing rectangle-shaped buildings – Printing head can reach the center of the work area	– Machine dimension wider than printing objects
Cylindrical	3	– Suitable for printing cylindrical-shaped buildings	– Nozzle cannot reach the center of the work area
Polar	5	– Suitable for printing cylindrical-shaped buildings	– Nozzle cannot reach the center of the work area
SCARA	3	– Suitable for printing cylindrical-shaped buildings	– Nozzle cannot reach the center of the work area
Delta	3	– Suitable for printing tall buildings – Printing head can reach the center of the work area	– Machine wider than printing objects – Restricted workspace in the bottom work area

freedom objects; however, equipment costs and limited workspace may reduce its applicability in large-scale architecture. The cartesian system could be applied to print large-scaled rectangular-shaped objects; however, the system width is greater than the printed object's width, which would require a robot bigger than the printed objects. While the cylindrical robot, is appropriate for printing cylindrical-shaped objects, it needs to be installed within the printing domain. Disassembling the system and moving it out of the building without damage to the printed objects may require extra effort. Although the characteristics of the polar robot, shown in Figure 2(b), are similar to those of cylindrical robots, its extendable arms may reach further to print larger objects. SCARA systems [Figure 2(c)] are famous for their fast movements; nevertheless, they may encounter the issues of the limited workspace. Finally, the delta suspension robot is suitable for printing tall objects; however, the system has a limited workspace near the bottom area. The selection of an appropriate robotic system of 3D concrete printing may depend on the printed objects' geometry, shape and height. Understanding the limitations and advantages of the robot system may help use concrete 3D printing benefits, such as economy, speedy, safety and ecology.

3.1.3 Nozzle. Nozzle properties such as cross-sectional shape, cross-sectional area and direction may influence printability. Printability is defined as the ability to stack concrete filaments. Regarding cross-sectional shape, some applications use round nozzle sections (Bos *et al.*, 2016), others adopt rectangle ones (Malaeb *et al.*, 2015). Both profiles are claimed to be able to deliver acceptable printability. The selection of the nozzle cross-sectional area may depend on the desired resolution. For large-scale AMoC, it could range from 13 mm^2 to 625 mm^2. The smaller the area, the higher the resolution that can be provided. While round nozzle sections do not have issues of nozzle direction, experimental results show that rectangular cross-sectional nozzles remaining tangent to the toolpath, as shown in Figure 3, while depositing concrete filament could derive better printability (Bos *et al.*, 2016).

3.1.4 Extrusion mechanism. To deliver a continuous concrete filament, nozzle moving speed and extrusion rate should have a perfect match. A pump or a mixing blade, as shown in Figure 4, can drive concrete extrusion. Due to the low flowability of concrete, pump pressure is frequently set at 1–3 MPa (10–30 bar) depending on the nozzle's moving speed, concrete viscosity, nozzle's cross-sectional area, length of the pipe and other relevant characteristics. For a mixing blade mechanism, the concrete extrusion rate is controlled by the speed of the spinning blade. A faster spinning blade could deliver a higher extrusion rate. Using the mixing blade, concrete extrusion could be interrupted when the mixing blade stops rotating or rotates reverses.

3.2 Material property

How to achieve printable concrete is one of the significant issues in AMoC. Slump is an index to measure the flowability of concrete. A zero-slump concrete may leave the nozzle as a relatively stiff continuous filament, which is frequently used in AMoC (Khayat *et al.*, 2019). Fast-dry cement is another material used to provide fast structural strength, with an initial setting time within 20 min. To further increase tensile strength, glass fibers are added to the concrete (Panda *et al.*, 2017). In addition, aggregates, sand superplasticizers, accelerators, retarders and additives are added to achieve the desired concrete functions.

3.3 Manufacturing process

This research focuses on the material extrusion manufacturing process, one of the most popular methods used in AMoC. While using the material extrusion method for concrete

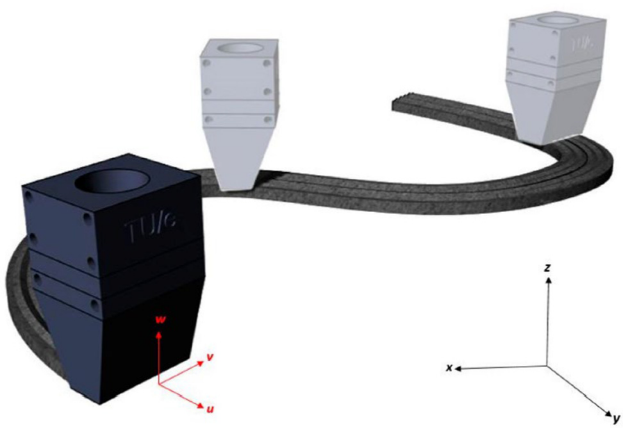

Figure 3. Nozzle rotation (Bos *et al.*, 2016). (reuse with permission from Taylor and Francis Ltd. www.tandfonline.com/toc/nvpp20/current)

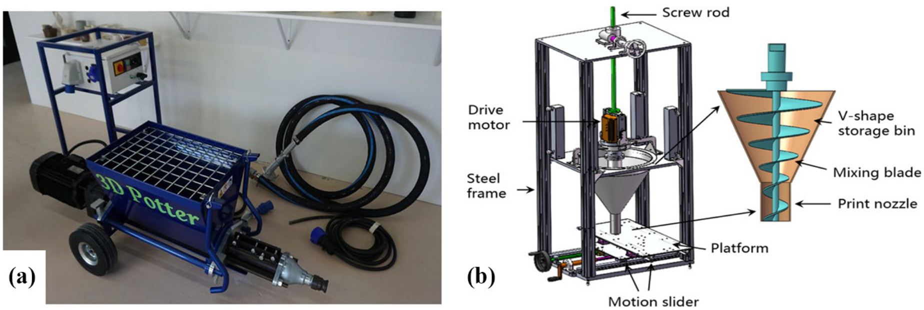

Figure 4. Extrusion mechanism. (a) Continuous flow pump (3D Potter) (reuse with permission). (b) mixing blade (Ma *et al.*, 2018). (reuse with permission)

printing, unlike plastic desktop AM, one of the most challenging issues is that there is no supportive structure while printing. This disadvantage may result in overhanging, bridging, uneven deformation and instability issues.

3.3.1 Overhanging. Overhanging, as shown in Figure 5(a), is caused by gravity for those elements without support structures. Due to the limited tensile strength of concrete before setting, deformation may occur at the overhanging end, as shown in Figure 5(b). In overhanging, uneven deformation may also be induced by shifting the center of gravity, as shown in Figure 5(c). The overhanging issue may constrain the curvature of the design. On the other hand, an overhanging design may not lead to a successful construction using concrete 3D printing. Understanding the overhanging angle (α), a maximum angle at which an overhang may not occur, as shown in Figure 5(d), is crucial for designing concrete 3D printing.

3.3.2 Compression. Concrete filament has weak mechanical strength before setting. While overhanging issues deform objects under tension, before the mechanical strength is generated, the self-weight of the concrete makes the filament thinner under pressure (Panda *et al.*, 2018). This feature may lead to bottom layers of filament subject to compression, resulting in a vertical settlement. Increasing layer cycle time, allowing time to achieve mechanical strength, may reduce this problem. However, it may deteriorate the production rate. In addition, if the layer cycle time is beyond the concrete's initial setting, cold joints exist between layers. Cold joints are known as interfaces between layers with weak mechanical strength and low water resistance. They may induce structural and water leaking issues for the long term.

3.3.3 Bridging. Bridging is another issue due to the low tensile strength of uncured concrete and lack of support structure. As demonstrated in Figure 6, a bridging effect may occur in the portion without a support structure when the concrete filament's self-weight is beyond its tensile strength capacity. The difference between overhanging and bridging is that the bridging is supported by two ends and overhanging is a cantilever.

3.3.4 Stability. Before concrete sets, the concrete filament's mechanical strength is weak. As a result, the printed object may be unstable, which means it may collapse due to its low

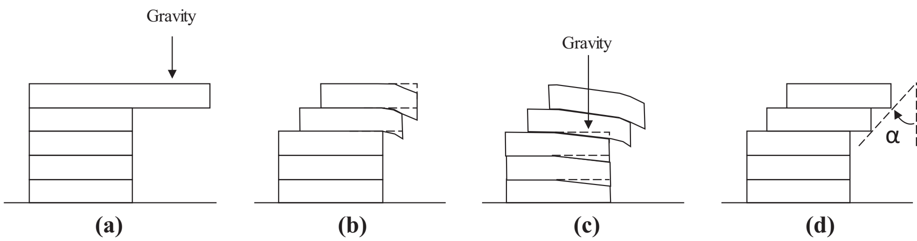

Figure 5.
Overhanging issues (exaggerated for demonstration).
(a) Gravity effect.
(b) Overhanging deformation.
(c) Uneven deformation.
(d) Overhanging angle (α)

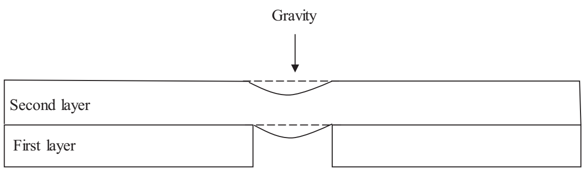

Figure 6.
Bridging issue

shear strength, as shown in Figure 7(a) (Le *et al.*, 2012a, 2012b). In addition, due to the lack of support structure, the printed object may tilt due to the shift of the center of gravity, as shown in Figure 7(b).

3.4 Control

AMoC selectively deposits concrete filament to construct objects in layers. The control of the nozzle's movement thus plays a crucial role in printability.

3.4.1 Inertia. In large-scale concrete 3D printing, the nozzle moving speed in linear motion may range from 50 mm/s to 200 mm/s. The mechanical speed could move faster than this. However, for a non-linear toolpath, the nozzle moving speed is reduced, depending on the curvature. Otherwise, the concrete filament may not be adequately deposited on the designated location due to inertia. While reducing or increasing nozzle moving speed, the extrusion amount and pumping rate are changed accordingly to maintain a stable extrusion flow. Another factor that may influence printability due to inertia is the rigidness of the printer. For a large-scale 3D printer, a floppy structure may incur an unwanted motion of the nozzle relative to the bed by the inertia, resulting in low printing quality.

3.4.2 Toolpath planning. Toolpath is a term defined in numerical control (aka Computer Numerical Control, CNC), which means the path that the tool head moves. As shown in Figure 8, different stacking strategies may result in different printability (Bos *et al.*, 2016). In Figure 8(a), the toolpath moves vertically from the first layer to the second layer with a continuous filament extrusion. A vertical filament is extruded during the layer transition. The vertical filament could be avoided if the nozzle stops supplying the concrete when moving toward the next layer, as shown in Figure 8(b). A continuous spiral filament, shown in Figure 8(c), could be generated if the nozzle gradually moves toward the next layer with a continuous extrusion. The selection of stacking strategy may depend on material property, desired texture and extrusion mechanism.

G-code is one CNC programming language used to control the toolpath. The toolpath planning on architecture may not be like that used in desktop fused deposition modeling

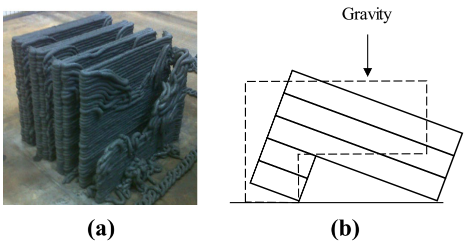

Figure 7. Stability issues. (a) Low stability due to weak shear strength (Le *et al.*, 2012b). (reuse with permission) (b) Tilt due to the shift of the center of gravity

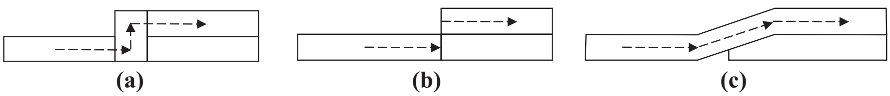

Figure 8. Stacking strategy. (a) Moving vertically with extrusion. (b) Moving vertically without extrusion. (c) Moving gradually with extrusion

(FDM). As shown in Figure 1, contour crafting is a typical method used to build a structure, while desktop FDM builds the thickness of the walls using parallel filaments with a hatching process. When using contour crafting, the toolpath sequence is crucial, i.e. outer box first followed by inner spiky-shaped "hatching." In this regard, general commercial slicing software may not be applicable to generate contour crafting G-code for architecture, such as residential buildings. As a result, developing G-code generators using computer-aided design (CAD) applications such as Grasshopper (Wolfs, 2015), as shown in Figure 9(a) or text programming languages such as MATLAB, C++ or Python, as shown in Figure 9 (b), are necessary for concrete 3D printing in architecture at the moment.

A shoulder effect describes a printer's head running into printed parts, thus damaging the printed objects. While planning the toolpath, the detection for shoulder effect could be adopted to avoid the damage.

3.4.3 Algorithms. The manufacturing process of AMoC could be optimized using algorithms. An algorithm is a sequence of the process used to achieve a specific task. For example, to increase the printed object's stability, the toolpath could place filament sections at various locations, giving them the time to cure before putting a new layer on top partially. An algorithm could be devised to place a segment, go somewhere else, place another segment and then return when the concrete started to set sufficiently to bind to the next layer and have more shear strength. Adopting an advanced algorithm, such as artificial intelligence, could enable a smart printing process (Yang *et al.*, 2017).

3.4.4 Multiple machines synchronous operation. One of the biggest limitations in the application of AMoC in architecture is that the size of the 3D printer must be larger than the building. This limitation makes AMoC applications impractical. One way to overcome this problem is to reduce the printed objects' size and then assemble these pre-printed small-size components during the construction phase. However, this approach may complicate the design work. In addition, the on-site assembly of components may greatly increase the time and cost required for construction, thus reducing the benefits of 3D printing, which can shorten the construction period and reduce costs.

Zhang *et al.* (2018) first used multiple 3D printing robots to print large-size building components (186 cm × 46 cm × 13 cm), as shown in Figure 10(a). Although the concept of simultaneous construction by multiple robots can overcome the limitation that the size of the 3D printing robot must be larger than the structure, this approach may need to avoid the problem of robot collisions. Nozzle trajectory planning, therefore, becomes the challenge of applying multiple 3D printing robots (Piker and Maddock, 2019). Furthermore, when multiple 3D printing robots work simultaneously, each robot works independently and does

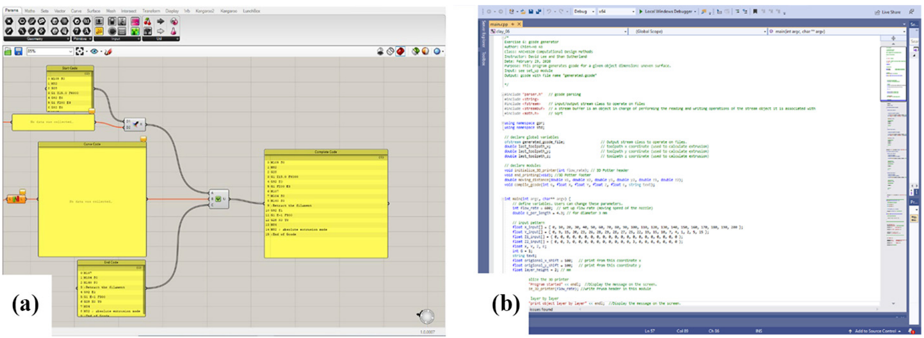

Figure 9.
G-code generators.
(a) Grasshopper.
(b) Microsoft Visual Studio C++

not really cooperate. To avoid robot collisions, the workspace between robots does not overlap. The application of multiple robots may result in multiple cold joints, reducing mechanical strength and printing quality, as shown in Figure 10(b) (Fok *et al.*, 2018).

3.5 Design for additive manufacturing of concrete

Design for Additive Manufacturing (DfAM) discusses printability, printed object function, printing resolution and economy of the printed objects from the design perspective. The process is to optimize the design according to the limitations and constraints of concrete 3D printing.

3.5.1 Geometry. Successful AM could not be achieved without supportive CAD. To integrate CAD and AM, i.e. CAD/computer-aided manufacturing (CAM) integration, constraints and AM limitations need to be considered in the design phase, namely, DfAM (Thompson *et al.*, 2016). Constraints and the limitations of AMoC, including overhanging angle, bridging distance, uneven deformation, stair-step effect, printing orientation and collision, could be analyzed by the object's geometry. The length of the concrete filament has a direct impact on printing time and cost. The economy could also be estimated by its geometry.

3.5.2 Architectural design. Architectural design for concrete 3D printing has not been fully discovered yet, as aesthetic design and site planning are subjective and primarily depending on human preference. Examples of site plan and building constructed using concrete 3D printing are shown in Figure 11 (Khorramshahi and Mokhtari, 2017; Szabo, 2018). While concrete 3D printing is a multidisciplinary field involving design, engineering, construction and automation, the design of AMoC becomes a time-consuming process. Unreasonable designs, such as overhanging and oversizing, may incur change orders, thus significantly reducing concrete 3D printing benefits.

3.6 Discussions

Although concrete 3D printing may provide a faster, cheaper, safer and more ecological building technology in architecture, various kinds of constraints and limitations may be encountered. The constraints may involve the type of the printer, software and control, manufacturing process and design. Each type of printer robot has its characteristics and may be suitable for different building geometry. To secure printability, a formula that could provide the concrete filament's stiffness and flowability may need additives such as a superplasticizer, accelerator and a retarder.

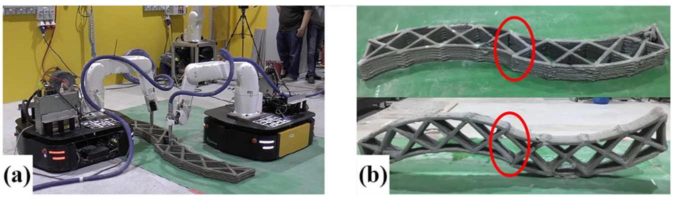

Figure 10. Multiple 3D printer robots. (a) Synchronous operation (Zhang *et al.*, 2018). (reuse with permission) (b) Cold joints (Singapore Centre for 3D Printing and CRI Group, 2018) (reuse with permission)

Tool path planning may be limited by stacking strategy, collision and shoulder effect. To obtain a practical design, a toolpath analysis could be carried out before construction. In addition, by using contour crafting technology, the slicing method used in the 3D building model is different from that of plastic FDM. As a result, G-code for AMoC may not be generated using software packages on the market. Instead, G-code for AMoC may be generated by CAD application or customized by specifically developed computer programs.

At present, in architecture, AMoC applications mainly use material extrusion or binder-jetting manufacturing processes. Other AM methods seem relatively unsuitable for printing large-scale buildings. The main limitation of the material extrusion approach is that it takes too long for the concrete to set, resulting in a small overhanging angle. This feature certainly limits the flexibility in architectural design. On the other hand, although the binder-jetting manufacturing method does not have the problem of overhanging, it requires tremendous powder for large-scale building printing. It seems impractical to use binder-jetting to build full-scale houses.

Architectural design for AMoC may involve multidisciplinary knowledge and skills, such as architectural design, AM, concrete property and robotics. Like designing wooden and brick buildings, the design methods are different when the material properties and construction methods are different. How to design the AMoC house has rarely been discussed. The popularization of 3D printing buildings must start with design. Without design, there is less chance to construct buildings using concrete 3D printers.

Although more and more AMoC projects have been proposed, they are still not common compared to wood, steel, brick and reinforced concrete structures. As the architecture projects involve residential safety, in addition to design and construction, it needs to comply with building codes. The current situation that lacks building codes for AMoC retains AMoC at the research stage.

Large-scale AMoC has only been developed for a few decades as it was first proposed in 1997. AMoC is different from traditional casting methods. The main difference is that in AMoC, the buildings are built in layers and material strength relies on adhesive between the filaments. In addition, to increase printability, 3D printing concrete adds additives that may influence concrete's long-term performances. Although concrete is a durable material, the impact of these factors on AMoC includes waterproof, earthquake resistance and weathering remains to be tested by time.

4. Conclusion

AMoC may provide a promising technology to overcome challenges faced in the architecture industry, such as labor shortage, high hourly wage and low productivity. However, constraints and challenges may be encountered while applying AMoC in architecture.

Figure 11.
Design for additive manufacturing of concrete (Khorramshahi and Mokhtari, 2017; Goukassian, 2018). (reuse with permission)

Understanding possible constraints and limitations of concrete 3D printing would help achieve successful AMoC projects.
Factors influencing the success of AMoC include hardware, material, control methods, manufacturing process and design. Considering these issues in the early design phase is crucial to achieving a successful CAD/CAM integration to bring CAD and CAM benefits into the architecture industry.

A breakthrough of AMoC in architecture may rely on new machines that hybridize the advantages of different robot systems. Besides, new concrete formula allowing a long span or providing a support structure for the cantilever and bridge may overcome the challenges that the roof and hypersurface may not be economically manufactured and assembled. Identifying materials other than concrete, which can provide better properties for printing architecture objects, is also worthwhile for future research. Besides material extrusion, other manufacturing methodologies, such as binder jetting, energy deposition, material jetting, sheet lamination and liquid photopolymer, could be investigated. Still, other issues await to be studied, including design for concrete 3D printing, aesthetic design, building and fire codes for concrete printed houses, efficient design, reinforced and embedding parts, AMoC construction management, building maintenance, energy efficiency, ventilation and insulation. This research does not touch on economic issues while applying concrete 3D printing, which is worth further analyzed in the future.

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