3D printing trends in building and construction industry: a review

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3D printing trends in building and construction industry: A review

Three-dimensional (3D) printing (also known as additive manufacturing) is an advanced manufacturing process that can produce complex shape geometries automatically from a three-dimensional computer-aided-design (CAD) model without any tooling, dies and fixtures. This automated manufacturing process has been applied to many diverse fields of industries today due to significant advantages of creating functional prototypes in reasonable build time with less human intervention and minimum material wastage. However, a more recent application of this technology towards the built environment seems to improve our traditional building strategies while reducing the need for human resources, high capital investments and additional formworks. Research interest in employing 3D printing for building and construction (B&C) has increased exponentially in the past few years. This paper reviews the latest research trends in the discipline by analysing publications from 1997 to 2016. Some recent developments for 3D concrete printing at the Singapore Centre for 3D Printing (SC3DP) are also discussed here. Finally, this paper gives a brief description of future work that can be done to improve both the capability and printing quality of the current systems.

Keywords: Computer aided-design; 3D Concrete printing, Digital construction; Automation; Building materials

Introduction

After more than 25 years of research, development and use, three-dimensional (3D) printing in various industrial domains, such as aerospace, automobile and medical, continues to grow with the addition of new technologies, methods and applications (Vaezi et al. 2013; Chua & Leong 2014; Huang et al. 2013; Gibson et al. 2010). One of such methods being explored currently, both in academia and in construction practice, is the 3D printing of concrete. Conventional construction process appears to be relatively simple and systematic; requiring two-dimensional (2D) drawings and scale models (for evaluation of the building designs), cumbersome formwork and much skilled labour to build any kind of freeform structures (Maas & Gassel 2005; Zavadskas

2010). Work-related injuries and illnesses pose a continuing threat to the health and well-being of construction worker (Kittusamy & Buchholz 2004). Construction industry continues to have higher rate of fatality, injury and illness than any other industries (Biswas et al. 2017, Meliá et al. 2008, Ministry of Manpower 2015). This compels the introduction of 3D printing to be coupled with building information modeling (BIM) for tracking and monitoring new variables introduces in a dynamic working environment such as a construction site (Bryde et al. 2013; Azhar 2011) to increase workplace safety. Combining BIM and 3D printing would also make it easier to create highly customized building components and facilitating complex and sophisticated design however, there are still numerous challenges related to scale, materials, delivery system and suitability to adverse environments.

Although work by researchers in the field of aerospace and manufacturing have shown that 3D printing could be the solution to reduce cost, there is no investigation to support that the same savings will apply to building and construction (B&C) industry. However, it is still appropriate to assume utilising 3D printing could minimise cost for the construction of B&C applications with aesthetic design based on cost analysis investigation done by researchers in other fields (Conner et al. 2014, Thomas et al. 2014).

Considering global demand to reduce CO_2 emission, there is a need for innovative construction technologies to not only pave the way towards a future of sustainable construction, but also to reduce construction and facilities management costs while providing a competitive edge. Construction formwork which typically accounts for 40% of the total budget for concrete work can be avoided during the building process, ultimately reducing the project timeline without incurring additional cost (Kothman & Faber 2016). With 3D printing technology, design of structures won't be limited to a collection of monotonous prefabricated elements.

This paper introduces the variants of concrete printing process under development around the globe and provides the latest research trend by analysing publications over last 20 years. Subsequently, the paper will highlight the ongoing research at Singapore Centre for 3D Printing (SC3DP) with possible topology optimisations and the significance of incorporating BIM. Finally, by analysing the trend, some future works are proposed can eliminate or reduce the challenges and limitations for 3D printing in B&C industry.

Current trend of 3D printing in B&C research

The interest in 3D printing for B&C has increased drastically in recent years. While the rise of interest has enriched the literature in this discipline, it presents challenges for researchers to capture an overview of the research development. Mapping the frequency of publications can be a way to understand the research trend. A systematic mapping studies as proposed by Petersen et al. (2008) shown in Figure 1 provides an overview of a research area and identifies the quality and type of research results available. It is important to examine the literature systematically for effective understanding of research development in the discipline as well as to serve as an inspiring source for research trend on 3D printing for B&C.

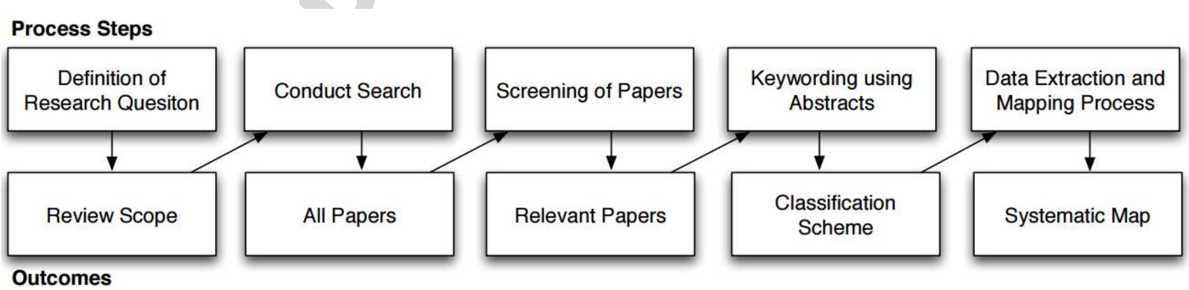

Figure 1. Systematic mapping system (Petersen et al. 2008).

Review data source and methodology

This review examines data based on two multidisciplinary databases of scientific research, Web of science and ScienceDirect. The combination of both database covers more than 12,000 journals and 160,000 conference proceedings. Boolean operator, quotes and parentheses were used to refine the search. Publications include only conference paper and journal articles with direct relation to 3D printing for B&C applications. Other publications such as book reviews, letters, theses, editorial materials and articles with irrelevant content were excluded in this study.

A total of 4,117 publications were found to satisfy the keywords used in the initial search for Web of Science. For ScienceDirect, 7,173 publications were found to satisfy the keywords in the initial search. However, only 3,211 publications were screened because ScienceDirect limits to show only the first 1000 articles (Table 1). Therefore, a total of 7,328 publications were screened for duplicates and filtered for relevance based on their title and abstract. Table 1 shows the breakdown of documents found during the search.

Table 1. Keywords used for an initial search performed on 18 January 2017.

No.	Exact words	With at least one of these words	None of these words	No. of documents found and screened in Web of science	ScienceDirect	
					No. of documents found	No. of documents screened
1	Rapid Prototyping	Construction Building Civil engineering Large scale Architecture Automation in construction	Biological Organ Food Medical Tissue	2,199	4,056	1,000
2	Additive manufacturing			984	1,647	1,000
3	3D printing			588	1,259	1,000
4	Digital fabrication			252	95	95
5	Digital construction			63	61	61
6	Contour crafting			16	26	26
7	Additive construction			7	24	24
8	Concrete printing			8	5	5
	Total number of article found for initial search including duplicates and irrelevant articles			4,117	7,173	3,211

Review results and discussion

A total of 115 publications were selected from screening and were subjected to classification based on the work presented. While screening the publications, innovative research studies were discovered such as jammed structures (Aejmelaeus-Lindström et al. 2016), robot-winding (Wit 2015), smart dynamic casting (Lloret et al. 2015) and brick laying automation. Although these studies have a tremendous potential impact on the construction industry, these studies do not fit into the objective of this paper and therefore were not included.

Characteristic of publication output from 1997-2016

Figure 2 shows the number of 3D printing for B&C related conference proceedings and journal articles published from 1997 to 2016. In the first 16 years of this study period from 1997 to 2012, there were 42 publications. From 2013 to 2016 there were 73 publications, which is almost double the amount published in the first 16 years which shows the interest in 3D printing for B&C applications started to rise significantly in that period.

From 1997 to 2006, there are noticeably more conference proceedings than journal articles. It is from 2009 onwards, that publications of journal articles start to increase at a faster rate than the conference proceedings, which exemplifies the initiative for more comprehensive and all-rounded work in this discipline.

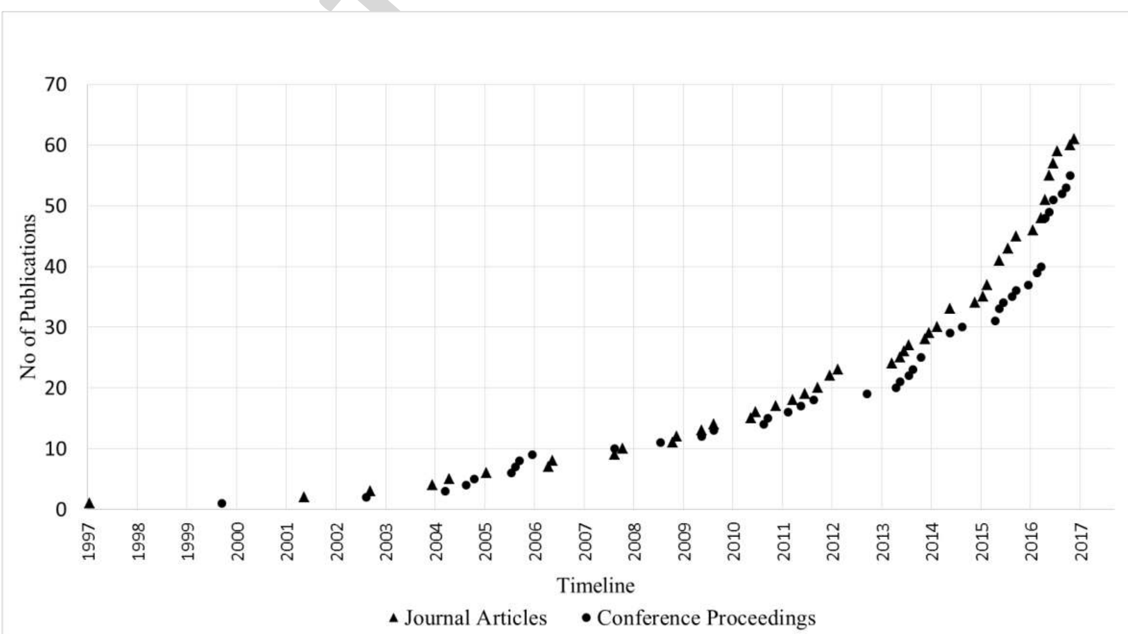

Figure 2: Trend of publication output over the years

Origin of publications

The contribution of publications from different countries was based on the affiliation of the first author only. An examination of the research origin of the identified papers as shown in Figure 3 indicates that USA and UK contributes the most in the field of 3D printing for B&C. About 49% of the total publications were identified from these two countries. Most of the publication from USA and UK are from University of Southern California, Loughborough University and Massachusetts Institute of Technology as they contributed the most publications in this field - more than 28% of the selected publication in this study.

From Figure 3, USA is the largest contributor to the 3D printing for B&C research; however, Figure 4 shows that the contribution from USA throughout the years remains somewhat constant whereas publications from all over the world have increased exponentially, especially in the last five years. The global trend of 3D printing in B&C research is accordant with the developmental trends toward scientific research globalization and other countries in the world are gradually reducing their disparities with the USA.

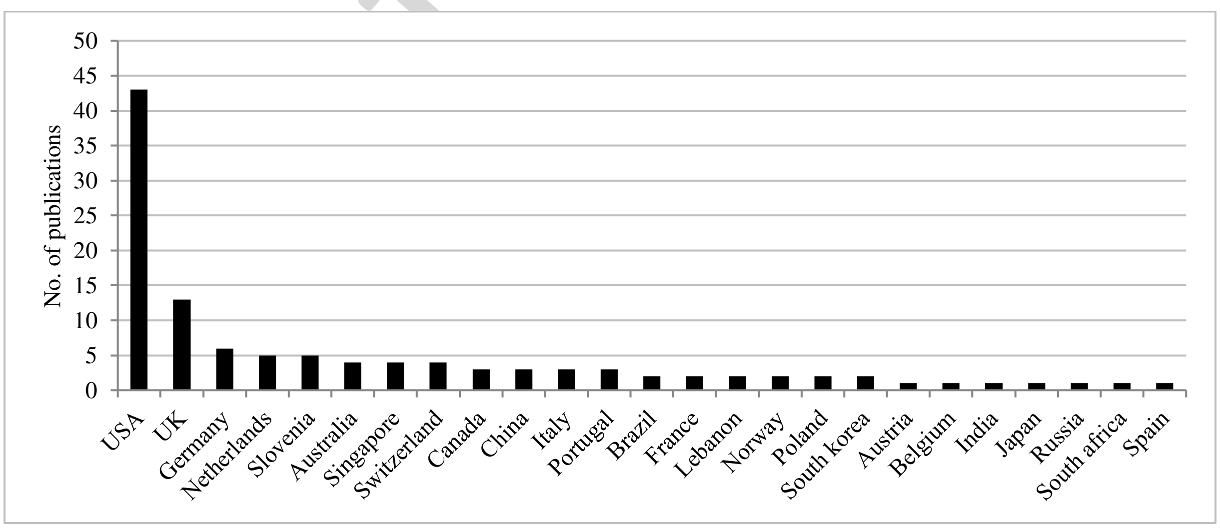

Figure 3. Research origin of paper published.

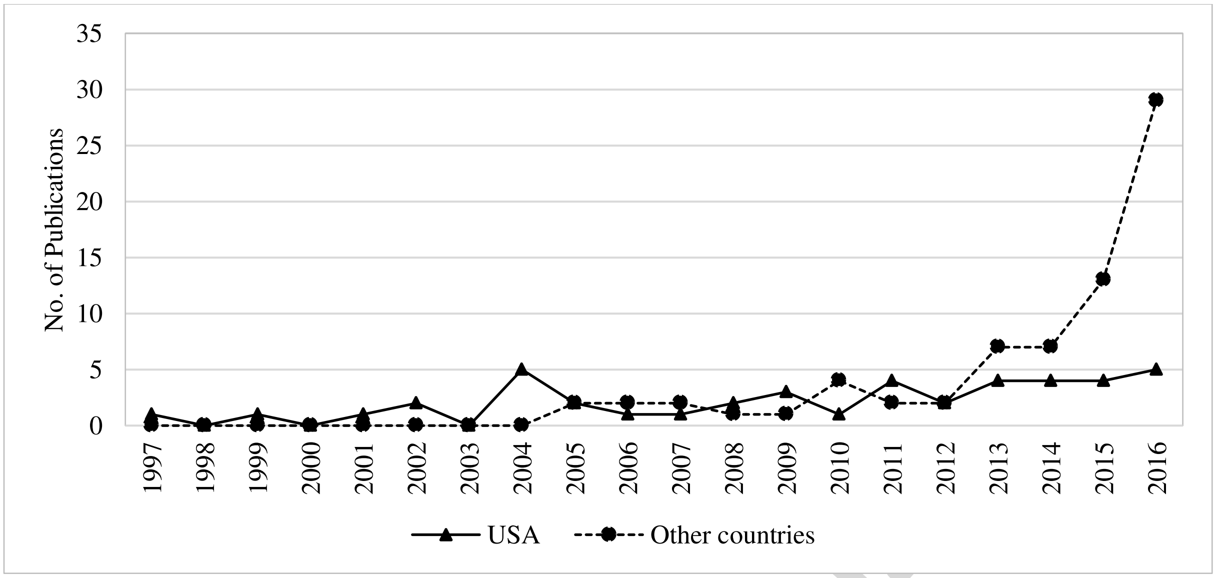

Figure 4. Comparison on the growth trend of USA and all others countries publications from 1997 to 2016.

Major research interest

Identified publications were classified to gain insights in the development trend of research in 3D printing for B&C. By examining the paper identified in this study, it can be observed that eight types of research interests were presented. Publications may be grouped into multiple research interest categories as the paper covers more than one research interest. It may be considered uncertain and subjective to decide which research interest represents the scope of each paper. However, any variation of views may be eliminated as the analysis was undertaken by the same group of researchers. Also, this study was conducted merely for comparison purposes; hence the approach adopted is believed to be appropriate. Detailed descriptions of each category are presented below.

(1) **Printing Techniques Analysis** refers to selected publications that include new nozzle, new method of extrusion, new method of delivery or methods that enhance the overall quality

of the print using a printer will be included in this category. Not limiting to only printing, new extrusion methods as described by Yoshida et al. (2015) will also be counted in this category. His work is included in Material Analysis and Architectural Design since material characterising work such as compression testing was presented and the geometry design was inspired by a harmonograph consisting of two damping pendulums.

(2) **Material Analysis** refers to the board and general process by which a material's structure and properties are probed and measured. In Perrot et al. (2015) work, data analysis was done after material characterizing to find the highest building rate for layerwise concrete 3D printing. Therefore, this paper contributes to both Material Analysis and Data Analysis.

(3) **Control System** researches on systems that control, direct, manage or guide devices to perform a specific task. An overall control system concept and kinematics equation for controlling of the cable-suspended subsystem has been presented by Williams et al. (2004). The work presented in this publication is a concept under development which can be included in Concept Analysis.

(4) **Data Analysis** presents on the ability of computer system or software to exchange and make use of information. It also depicts ways in which the model information is processed to produce a physical object.

(5) **Architectural Design** refers to publications that present components or elements of a structure and unifies them into a coherent design arrangement and functional whole. Some examples of Architectural Design were not fabricated using layer wise printing, thus able to demonstrate curvature of object otherwise not possible by conventional printing method (Lim et al. 2016).

(6) **Literature Review** includes publications such as review articles or research previously done by others. An example of a literature review is demonstrated by Perkins & Skitmore (2015).

(7) **Concept Analysis** reveals results that broadly enhance an understanding of the concept and its theoretical and practical implications for 3D printing in B&C. Concept analysis usually includes works that are under development or viable methods that lack in funding or opportunity. Such work can be found in (Williams et al. 2004) and (Kading & Straub 2015).

(8) **Cost-Benefit Analysis** reveals the cost and benefits of 3D printing for B&C activities. It is a process which sums up the benefits and subtracts the associated cost. Benefits may include an increase in productivity, building complexity, lower investment cost and reduction in waste. Costs may include direct and indirect cost, opportunity cost and cost of potential risks. A cost-benefit analysis done by Buswell et al. (2005) shows that the 3D-printed products are more suitable to compete for customisation rather than mass production.

Due to the limited amount of publications, results in table 2 and 3 have been grouped and shown for every 2 years. The two main research interests, comprising 45% of the total interest recorded are Printing Technique Analysis and Material Analysis. These publications demonstrated improvements to the usual Cartesian gantry or robot, such as swarm printing to expedite the printing process and cable robots (Oxman et al. 2014; Capua et al. 2014). Material Analysis research aims at both improving surface finishes and producing functionally graded components were also of much interest (Kwon et al. 2002; Craveiro et al. 2013). Attempt to characterise printable construction materials have been done (Le et al. 2012; Nerella et al. 2016) which all contribute to the research interest of Material Analysis.

Interest in architectural design, literature review and cost-benefits analysis sky-rocketed in the last few years are shown in Table 3. As the printing technique and material characteristic improve, the ability to create unforeseen structures will also improve. Publications such as (Lim et al. 2016) and (Garcia & Retsin 2015) are exploiting their material properties that never seen before. A doubly curved print which is not only aesthetically pleasing but of a higher quality than printing on a flat surface (Lim et al. 2016). Similarly, the work presented by (Garcia & Retsin 2015) consists of creating freeform mesh structures using quick-drying plastic material.

Table 2. Major research interest in the period from 1997 to 2016.

	1997 & 1998	1999 & 2000	2001 & 2002	2003 & 2004	2005 & 2006	2007 & 2008	2009 & 2010	2011 & 2012	2013 & 2014	2015 & 2016	Total
Printing Technique Analysis	1	1	3	5	4	3	7	4	12	18	58
Material Analysis	1	0	2	1	2	0	4	8	10	18	46
Architectural Design	0	0	0	1	1	1	3	4	4	15	29
Literature Review	0	0	0	0	2	0	1	0	4	17	24
Data Analysis	0	0	1	2	0	3	2	0	6	9	23
Control System	0	0	0	1	0	2	2	0	5	8	18
Cost-Benefits	0	0	0	0	4	2	0	0	1	9	16
Concept Analysis	0	0	0	1	1	1	1	2	5	4	15

Table 3. Frequency of keywords used in publication titles.

	1997 & 1998	1999 & 2000	2001 & 2002	2003 & 2004	2005 & 2006	2007 & 2008	2009 & 2010	2011 & 2012	2013 & 2014	2015 & 2016	Total
3D printing	0	0	0	0	0	0	1	1	6	13	21
Concrete	0	0	0	1	0	0	0	2	5	13	21
Contour Crafting	0	1	3	2	3	2	2	0	1	2	16
Freefrom	1	0	0	0	4	0	3	0	1	1	10
Additive Manufacturing	0	0	0	0	0	0	0	2	2	6	10
Rapid Prototyping	0	0	0	1	0	1	0	3	1	2	8
Large-Scale	0	0	0	0	0	0	0	0	1	7	8
Construction Material	0	0	0	0	0	0	0	0	1	2	3
Mega-Scale	0	0	0	0	2	1	0	0	0	0	3
BIM	0	0	0	0	0	0	1	0	1	0	2
Digital construction	0	0	0	0	0	0	0	1	1	0	2
In-Situ	0	0	0	0	0	0	0	0	1	1	2
Lunar Soil	0	0	0	0	0	0	1	0	1	0	2

Analysis of publication titles

The title of an article contains a concise group of selected words expressed by the author for the interested reader. In this analysis, the 13 most frequently used words were chosen and reported in Table 3. Along with the growth in the number of articles, the presence of target words such as “3D printing”, “concrete”, “large-scale” and “additive manufacturing” seem to increase as well. “Concrete” only recently started appearing frequently in publications due to the material’s increase in use for 3D printing.

Alternatively, the use of words such as “mega-scale” and “freeform” seems to have reduced in the past decade. A possible explanation for the decrease in ‘mega-scale” is that this word may have been substituted by the “large-scale”. Another explanation could be the gradual disregard of these words by researchers. For example, the work demonstrated by Gosselin et al. (2016) shows that printing certain "free-form" structures using material extrusion is not possible, as large angles and cantilevers cannot be printed.

The information revealed in this study is valuable to the researchers interested in understanding key trends of research development in 3D printing for B&C sector. Although, the two databases selected may not contain all related publications in 3D printing for B&C works, the papers identified in the reflect the general trend of 3D printing for B&C research.

State-of-the-Art technologies for 3D printing in B&C

The rapid development of large-scale 3D concrete printing technology in most literatures are categorized into two techniques, namely:

1. Binder jetting 2. Material deposition method (MDM)

The basic principle of both these techniques is to build up any complex structure by adding small layers of material one over another. It begins with the creation of a 3D CAD model, which is sliced into several 2D layers and then printed with an assigned material in an incremental manner to obtain the prototype as described in the CAD model. Out of the 115 publications identified, only 12 publications focus on binder jetting.

Binder Jetting

Binder jetting is a 3D printing process that creates objects by depositing binder layer by layer over a powder bed. Binder is ejected in droplet form onto a thin layer of powder material spread on top of the build tray. This method incrementally glues 2D cross sections of the intended component to each layer of material powder (Perkins & Skitmore 2015). The cycle repeats until the whole 3D object is complete (Figure 5a). Any raw material that is not glued by the binder remains inside the constrained build container and is used to support subsequent layers. The unbound material can be removed from the print bed using a vacuum cleaner after the printing, which can be recycled and deployed for another printing task (Khoshnevis et al. 2006). This method encourages designs to have voids and overhanging features which enable the printing of complex geometries. It has a relatively high resolution that results in the good surface finish because of the minimal distance between layers. This layer thickness value is determined by the penetration of the binder. If the layer thickness is too large, the binder may not penetrate deep enough to glue the current and the previous layer together (Cesaretti et al. 2014). Currently, Voxeljet and Monolite UK Ltd (D-Shape) are working with this technology to print large-scale components for architecture and building industries. Figure 5b shows an egg shape complex sculpture, made by D-shape using a sand-based material; however, this technique can be easily influenced by bad weather, and is difficult to use this process for in-situ construction applications (Dini, 2009).

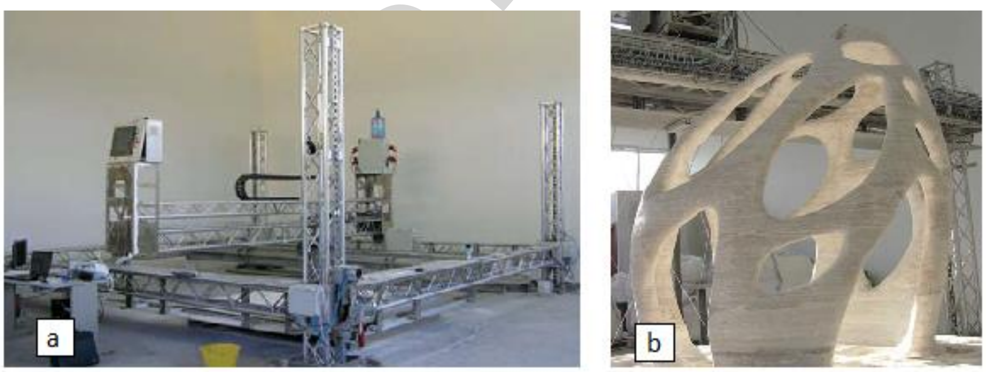

Figure 5. (a) D-shape printer (b) Final printed component with all the excess raw material removed (Dini 2009)

Material Deposition Method (MDM)

Similar to fused deposition modelling (FDM), material deposition method (MDM) is a 3D printing processes that successively lays material as per the CAD model (Panda et al. 2016). The extruded material must be able to support its own weight and the weight of each subsequent layer to attain the final design without any deformation (Hwang et al. 2004). There are several automated systems that use MDM as their core fabrication process and they are explained as follows:

Contour crafting (CC)

Contour crafting (CC) is a gantry based system that extrudes material in a layer by layer manner. The key feature of CC is the use of trowels attached to the nozzle. The trowel guides the printed material to create exceptionally smooth and accurate surfaces as shown in Figure 6. This trowel can be deflected at different angles (by computer control) to create various non-orthogonal structures. Such approach enables a deposition of higher layer thickness without significantly compromising the surface finish (Khoshnevis 2004). Figure 7 displays contour crafted structures made from ceramic and concrete material. The detailed material composition and printing procedure are described in (Hwang & Khoshnevis 2005; Lim et al. 2011). It is also reported that printed walls with embedded conduits for both electricity and plumbing as well as structural reinforcement can be achieved through CC (Khoshnevis, 2004).

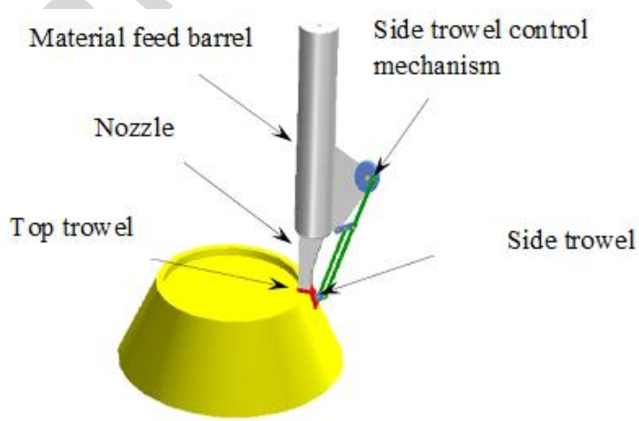

Figure 6. Contour crafting process (Khoshnevis 2004)

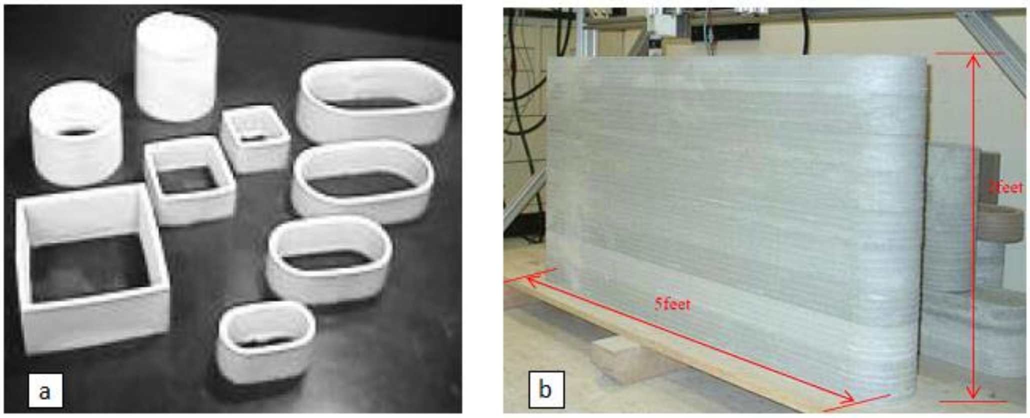

Figure 7. Contour crafting using (a) ceramic and (b) cement material (Hwang & Khoshnevis 2005; Lim et al. 2011)

Stick Dispenser

Stick dispenser is a specially designed hand-held printing device that enables a consistent feed of chopstick material composites developed by Yoshida et al. (2015) shown in Figure 8a. In this process, chopsticks coated with wood glue are dropped randomly forming an aggregated porous structure that is later evaluated through volume-based analyses. The stick dispenser is guided by a depth camera and a projector in real time. Both these tools assist in informing where the chopsticks are being deposited by projecting a simple colour code. Printing must be done in low-light condition for operating the projector. Figure 8b shows a pavilion assembled from separate panels made using this method. The mechanical properties of the printed samples are acquired by performing different load tests. The results show that such printed structures do not have any load bearing capabilities but are innovative in their process of building complex architectural designs for aesthetic purposes.

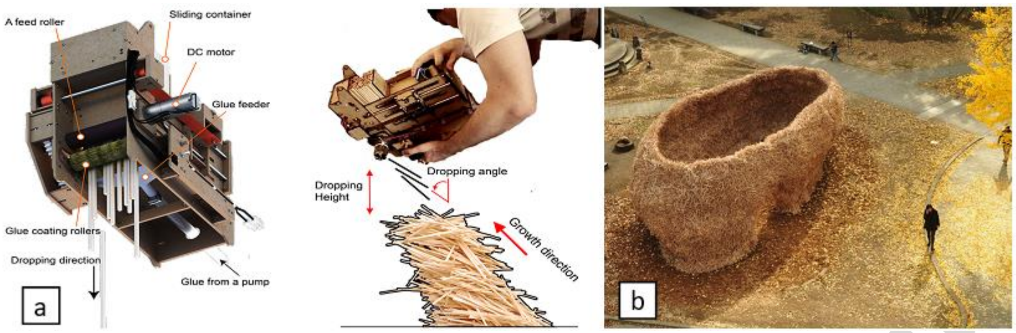

Figure 8. (a) Stick dispenser (b) Constructed pavilion using chopsticks

Digital Construction Platform

This is a system used for on-site sensing, analysis and fabrication built by a group of researchers at Massachusetts Institute of Technology (MIT) (Keating et al. 2014). This system is designed around a large boom, which is used for gross positioning to increase speed, accuracy and ease of access with a small robotic arm. Using ground reference sensors and an accelerometer allows the closed-loop system to accurately position the end effector. In this system, polyurethane foam is used as the material for printing because of its rapid cure time and its high insulate value. Printing a wall of a twelve-foot long dimension would only take five minutes. Besides being used for printing, the end effector is interchangeable and can be switched to a mill head for a subtractive manufacturing process if a finer surface finish resolution is desired.

Concrete Printing

Concrete printing, which is similar to CC, is a system built by the researchers at Loughborough University, UK (Lim et al. 2012; Le, Thanh et al 2012) that extrudes concrete layer by layer following a digital model. The setup includes 5.4m x 4.4m x 5.4m (L x W x H) gantry printer as shown in Figure 9a. Certain terms are used to describe the flow of material deposition in this method due to the fresh properties of the concrete. “Over-printing” is when too much material is deposited at a specific point, causing unnecessary bulging of the printed part. “Under-printing” is when there is a lack of deposited material at a point which may cause breakage during printing. These problems however, can be addressed by fine-tuning the machine operating parameters or modifying the tool path.

Most MDM is categorised as flat-layered printing. Flat-layered printing extrudes material in a two-dimensional plane layer by layer until it reaches the desired volume. This printing method creates mechanical weaknesses such as anisotropic properties and creates visual issue such as staircase effect on the completed print surface. Recently, Lim et al. (2016) introduced another method of curved-layered printing. Curved-layer printing improves the aesthetic and mechanical properties of a printed part (Lim et al. 2016). Figure 9b shows a concrete panel printed on a non-layered panel.

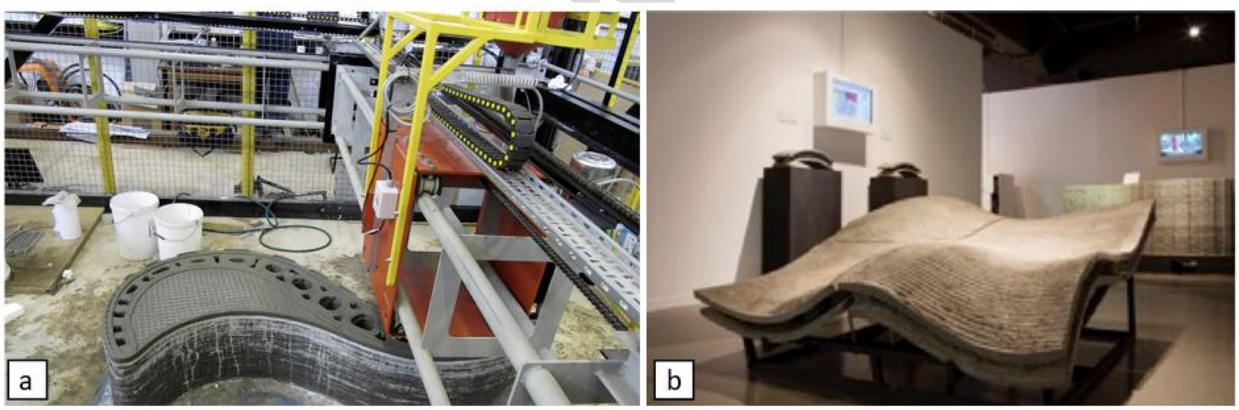

Figure 9. Concrete printing at Loughborough University (Le et al. 2012).

Flow-Based Fabrication

Researchers at MIT designed a system to extrude water-based polysaccharide gels and natural composites with a single pneumatic extrusion system attached to the end effector of a 6-axis robotic arm shown in Figure 10. The hierarchical structuring of printed part is designed and fabricated in 2-dimension (2D). The design and advance manufacturing of heterogeneous materials and anisotropic structures will result in high stiffness, lower weight, high wear and resistance (Duro-royo et al. 2015a). New applications for this work ranges from automated construction of architectural facades with different translucency to temporary lightweight shading structures.

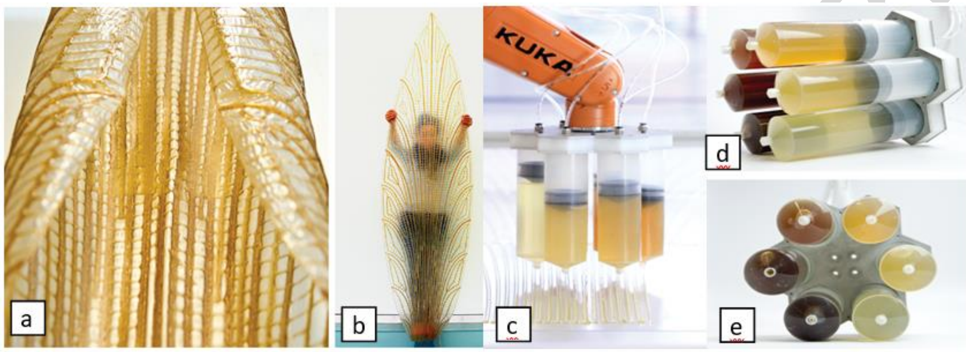

Figure 10. Large-scale hierarchically structured chitosan-based deposited construct (Duro-Royo et al. 2015b)

Minibuilders

A coordinated system of three individual robots is built for fabrication of in-situ construction. They are lightweight, compact and have autonomous mobility. Each robot has a different function during the printing process as described in detail by Nan (2015). A two-component resin material was developed for these robots as the movement and speed of the robot determines the extrusion rate. If the material's curing time is not compatible with the flow rate and the robot movement speed, the material may clog in the hose. An additional heat source can be added depending on weather conditions for expediting the chemical reaction and reducing the curing time of the printed material.

Mesh mould

This technique utilises a large 6-axis robot to extrude thermoplastics polymer to print in-situ structures freely in 3D space. Pinpoint cooling using pressurised air at the nozzle during printing allows for a high level of control thus facilitating the weaving of wireframe structures freely in space shown in Figure 11a. In this application, the structures act as reinforcement for the concrete. Concrete is then poured over this formwork and later trowelled manually to smooth the surface (Figure 11b). Using such methodology reduces the time required for fabrication of complex structures which becomes feasible for large scale applications. Different density of mesh can be printed (Figure 11c) according to the array of forces acting on the structures. More interestingly, the presence of the mesh increases the tensile force of concrete ultimately becoming a possible replacement of conventional steel reinforcement.

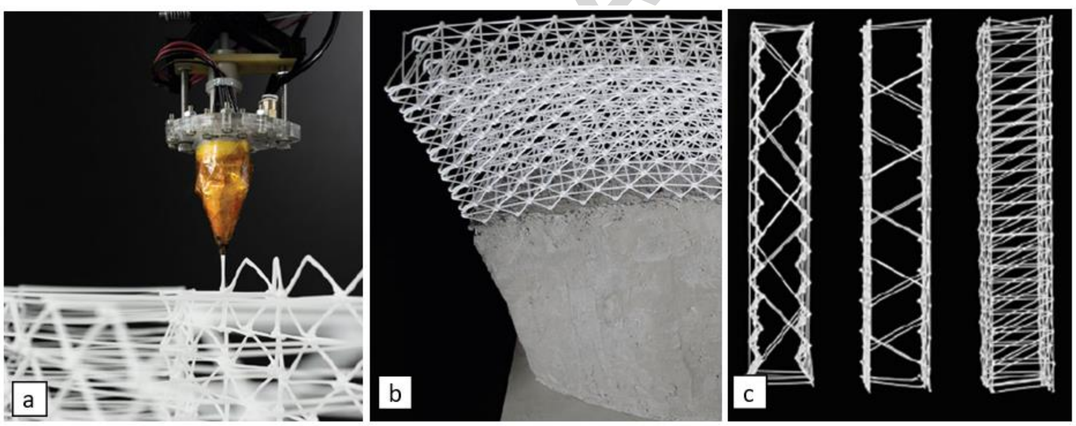

Figure 11. Mesh-mould combines formwork and reinforcement system for concrete (Hack & Lauer 2014)

Building Information Modelling (BIM)

Building Information Modelling (BIM) is a comprehensive approach towards building construction management which covers the complete life cycle of the construction process (Eastman et al. 2011) such as construction planning, scheduling, estimation and post construction facility management. The construction industry has always been criticized for low productivity and lack of collaboration and innovation in its execution process and BIM has shown potential to be a viable solution for these issues (Elmualim & Gilder 2013; Arayici et al. 2012).

In addition to the geometrical data BIM also contains material, equipment, resource and manufacturing data (Wu et al. 2016). This information data helps to address the issue of lack of collaboration between various teams in the project execution and serve as the base for integration of automation application such a 3D printing, robotic construction.

A BIM-based process flow for 3D printing can significantly reduce the overall process lead time by integrating each step and make it executable through a single interface or software. This could address the issue of the constant design changes which is relatively common in the construction industry. Since 3D printing as a versatile method does not require formwork, it is able to accommodate design change or faster change management in the final output without incurring much losses compared to other conventional processes. BIM can also aid in automating the entire printing process as it can store and synthesize equipment and manufacturing data such as printer control data, material delivery system and post finishing operation.

BIM is seen as a prime design language in the construction industry and could become the standard method to be followed throughout the industry. As 3D printing is also considered a game changer for the industry, a BIM-based 3D printing can be a method for the construction industry to look forward in the near future as it can bring obvious benefits and substantial savings in cost and labour. Usage of BIM for 3D printing is still not practiced widely and more research on this topic is needed to bridge the gaps between BIM and 3D printing.

Concrete Printing Research at SC3DP

Current research at SC3DP aims at developing new printable materials such as geopolymer mortar, lightweight mortar and fibre reinforced mortar for concrete printing applications. Additionally, recycled glass aggregates and crushed rock dust (basalt) are also being tested to enhance the formulation for sustainable construction. Different setups and analysis have been performed to scrutinize the properties and suitability of these materials. Below section describes our research activities which are devoted towards development of both machines and material for concrete printing application.

3D Concrete Printing at SC3DP

Two types of printers, four-axis gantry (Figure 12a) and six-axis robot (Figure 12b) are widely used in 3D concrete printing application (Nerella et al. 2016; Wolf 2015). Typically, for large scale printing, the gantry is more suitable due its simplicity. However, for printing complex objects, the robotic printer is more practically suited due to its 6-axis rotational ability. Figure 13 shows the capability of printing complex structural object at the SC3DP using both gantry and robotic printers.

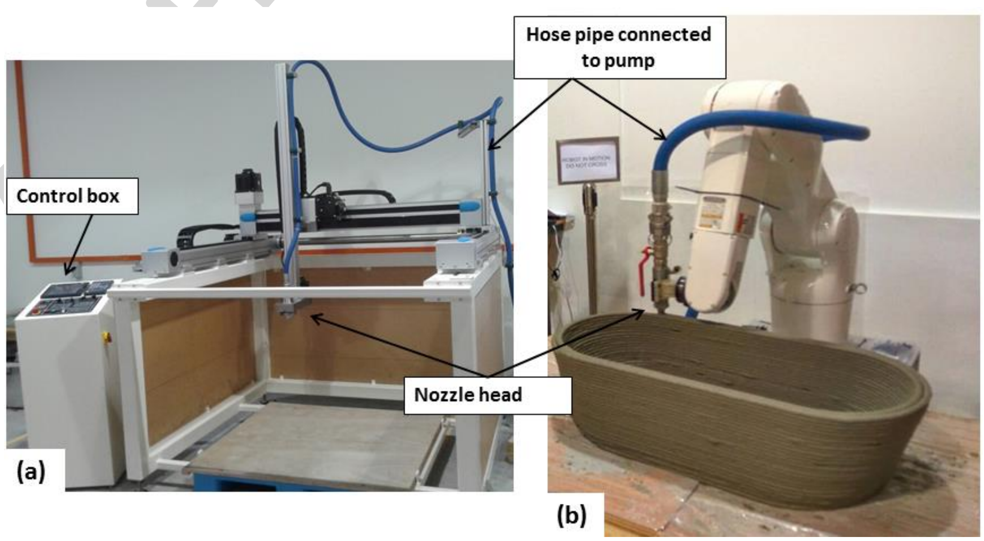

Figure 12. 3D concrete printers at SC3DP a) four-axis gantry and b) six-axis autonomous robotic printer

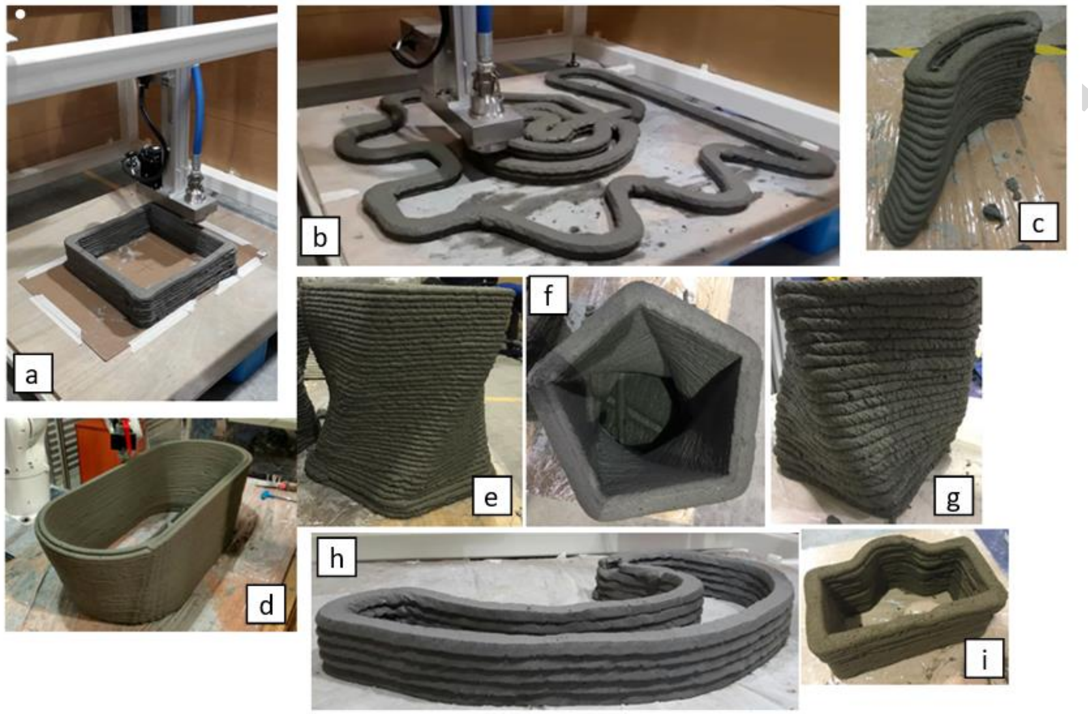

Figure 13. 3D concrete printed objects at SC3DP (prototype)

Material research at SC3DP

In SC3DP, the development of 3D printable materials is a major objective. Researchers are habitually performing various types of tests such as rheology spanning hourly time intervals to determine the stress and viscosity development (see Figure 14a). The plate staking test is used to measure slump deformation (see Figure 14b) while other tests are being conducted to determine setting and hardening behaviour of materials after the mixing. With these established parameters, properties such as required pump pressure for the materials, suitable printer speed and maximum bead layers of the printed objects are accounted prior to printing (Tay et al. 2016).

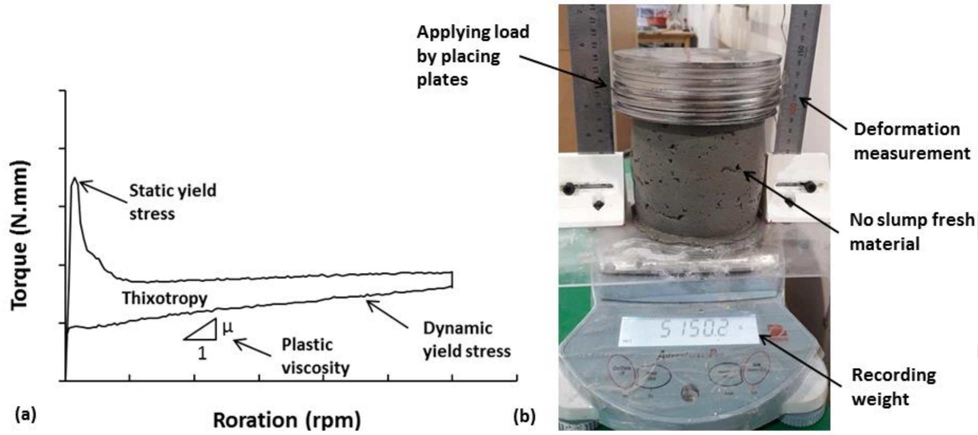

Figure 14. a) Rheology test using applied torque at different rotation and b) strength development test in fresh 3D printable concrete

One of the main disadvantages of 3D printed structures is that they carry both isotropic and anisotropic properties when oriented in different directions unlike in casted specimens where the properties of a material are even distributed in all directions. To investigate these multi-directional mechanical properties of a concrete 3D print, sections are cut and extracted from a large printed object and then tested for compression, flexural and tensile strength in the x y and z directions, as shown in Figure 15. In consecutive layer by layer printing of exothermic materials like concrete, the bond strength between the layers is very important. Our preliminary results shows that the loading in Y direction have the highest compressive strength and the bond strength between layers are higher when the time interval is short. In conclusion, it became evident that the print's mechanical properties are a direct response to parameters such as material viscosity, printing time gap between the layers and contact area between the successive bead layers.

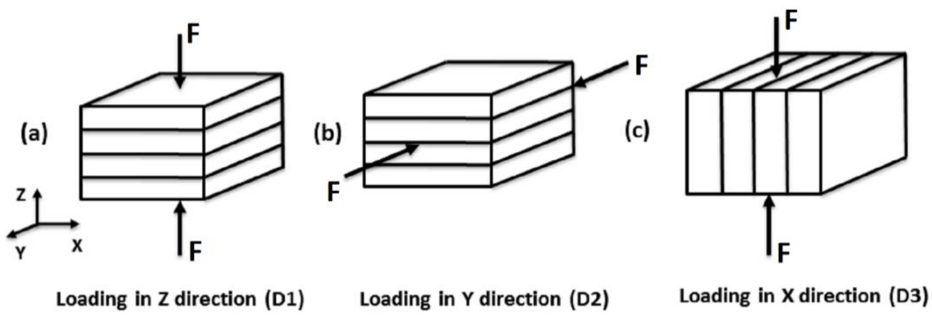

Figure 15. Three directions test for mechanical properties of 3D printed specimen

Architectural/ Topology optimisation

As the B&C group in SC3DP continues its research of concrete 3D printing for habitable building components and architectural spaces, it is important to iterate through and assess the results of structural topology optimization results for the redispersement or removal of unnecessary material resulting in optimal performance as well as material usage efficiency (Zegard et al. 2016) - a direct relation to cost efficiency. Prior to the 3D concrete printing process and after concluding at a final digital design, it is advised to undergo certain physics simulations of the form and material. Topology optimization and finite element analysis software are necessary tools for assessing both structural and fresh material implications for designed objects.

Concrete is a material that is extruded in its fresh state and it does not harden right away. Such material properties limit the complexity of topological design and extreme overhang structures is not printable without supports (Brackett et al. 2011). Finite element simulations with material property input can assist in understanding how the material will act. Physics engines can generate the contouring extrusion process while informing strains and buckling occurrences.

Future directions and research gap

This section highlights some of the possible future studies and research gap for the researchers to explore so that our traditional construction industry can properly take the full benefits of the 3D printing process.

Multi-nozzle integration

Introducing multiple nozzles integration or swarm intelligence could revolutionise the whole process of 3D printing. The multiple nozzles can be mounted on the existing single nozzle printers to print certain areas of the building component in the shortest time. However, the integration and communication of the multiple systems working together is complex and requires proper planning. Furthermore, integration of multiple nozzles can be useful to deposit different materials (as per the functional requirements) in part of the hybrid construction.

Hybrid 3D printing systems

Development of hybrid 3D printers for printing concrete structures with various materials and components such as reinforcement (for structural rigidity), different grade of materials for structural and non-structural application can be explored for future B&C projects. For continuous monitoring of the building elements like façade which is exposed to the different exposures, some sensors and actuators may be merged with 3D printing i.e. sensors can be embedded in the materials during printing. Embedded sensors will allow building health to be monitored in real-time even during the construction phase (Jiang & Hojjat 2007). Besides sensors, reinforcement can be printed with concrete to enhance structural designs to be more effective against any kind of loading.

Local Composition Control

Local composition control (LCC) is a processing to tailor material composition to obtain optimum monolithic components. Such components are known as functionally graded materials and some of the advantage includes saving of part count, space and dead-load of the building (Cho et al. 2002). LCC are more commonly used in binder jetting technology because un-used powder can be used as a support structure which makes the control of composition locally easier. However, tailoring the part's physical properties on a two-dimensional level for extrusion based printing can also be carried out thus do not require support structure.

Development of new material

Developing material for 3D printing process is a challenging task. Still several authors have printed nice concrete structures using different combination of cement, sand, flyash, silica fume and micro-fibres (Lim et al. 2012; Le et al. 2012; Nerella et al. 2016; van Zijl et al. 2016). The future success of 3D printing in B&C will depend on fine-tuning materials to specific needs of each application. Printing functionality added material, such as lightweight, thermal insulated, self-healing, self-sensing add value to the complex structures (Mahamood et al. 2012; Bekas et al. 2016; Park et al. 2015). Although, 3D printing is believed to have the right potential to print complex structures, eventually new printable material developed for each application will be scrutinize for high quality, low construction cost and brings value to the user.

Reinforcements

Another challenge for 3D printing in B&C is the counteracting of concrete low tensile strength and ductility. Addition of steel reinforcement to the concrete would solve the problem. However, in 3D printing, addition of steel reinforcement automatically is not so straight forward.

Both imbedding reinforcements demonstrated by Khoshnevis et al. (2006) and post-tensioning reinforcement bar demonstrated by Lim et al (2011) are inserted manually. Printing structures with straight hollow voids for post-tensioning reinforcement bar would limit the freedom of the architectural design.

Attaching a steel extrusion gun similar to a staple gun at the back of the nozzle and could enhance the tensile strength in the vertical direction. However, there will be a challenge to control the force of the steel staple penetrating the filament. If the force of the penetration is too large, it could deform or destroy the fresh concrete, if the force is too small, there could be no penetration at all. Addition to the steel reinforcement, inclusion of fibers may improve the ductility of the concrete (Figure 16).

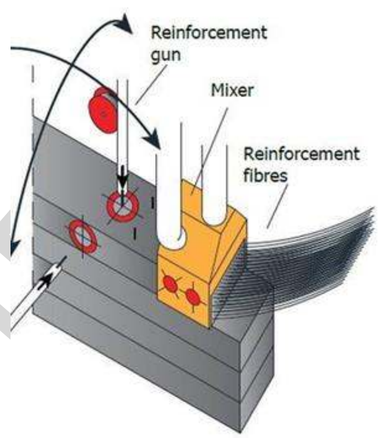

Figure 16. Reinforcement for concrete printing (de Witte 2015)

Process parameter optimizations

Process parameter such as the change of print speed, different layer thickness and flow rate due to the materials thixotropy properties plays an important role for concrete printing (Bos et al. 2016). Any inappropriate selection of parameter may result in bad quality print and sometimes can lead to catastrophic failure. For extrusion based printing like MDM, if the flow rate is not properly matched with printing speed, inconsistency in the layer thickness (sometimes more and sometimes less material) may occur, which will not allow high buildabilty for the printed structure. The main limitation of the 3D printing process is the layering effect which produces uneven surfaces with void in between the layers. Literature reveals that proper selection of layer thickness can reduce this effect; however, small layer thickness may need more printing time to build the whole structure. Therefore, tool path optimization must be carried out while considering build time, printing time gap between layers and surface finish as output variables (Jin et al. 2014). Alternatively, post-processing (grinding or plastering) can be done to improve the overall surface quality of the final product of 3D concrete printing.

Life cycle assessment (LCA) and Life cycle cost analysis (LCCA) of concrete printing

Construction is one of the industries that are responsible for high environmental impacts. Although concrete printing promise to deliver a greener and low-waste type of construction process, few attempts had been made to assess and compare environmental consequence of this technique to conventional construction. Work by Habert & Agusti-Juan (2016) highlighted the importance of material-efficient design to achieve high environmental benefits in digital fabricated architecture. However, their work did not target towards 3D printing but more towards digital fabrication. Ultimately, the purpose for LCA is to assess the environmental impacts associated with all stages of the product life and provide insights to the environmental improve 3D printing can deliver, of which both are lacking in the current research.

Besides the environment, there is also a lack of fundamental understanding of the economics that this technology could offer. Early implementation of cost analysis model in a project helps to associate the relation between cost and design parameters. The objective of LCCA is to provide a framework with an intention of reducing the total cost of design, development, production, use and disposal of the fabricated part (Senthil Kumaran et al. 2001). Introduction of

3D printing into the consideration of LCCA of a project allow an alternative solution to be considered for maximum net savings. An example would be to determine if the structural beam should be printed or casted in order to reduce the overall cost of construction and maintenance.

Safety and skills for 3D concrete printing

One of the most momentous challenges in infrastructure site is construction worker's safety. Studies have shown that the main risk source onsite are collision with machine, falling and machine running over, therefore these have to be taken into consideration when designing preventive security systems (Abderrahim et al. 2003). During printing, physical barrier is necessary to remove human activity around moving parts of the printer to prevent unnecessary collision. Safety monitoring system such as real-time video camera could also be mounted on the printing system to enhance proactive safety management for reducing accident on worksite (Zhou et al. 2013).

Another challenge for 3D concrete printing is that it requires skilled workers with experience to integrate robotic and civil work together. The knowledge on the printing parameter and thixotropic properties of the material plays a crucial role on the quality and limitations of the architectural design. The 3D printing industry is expecting to grow at a staggering percentage by 2020. Therefore, existing worker in the conventional methods may require re-training or may find themselves moving on to other jobs. Much research is needed to better understand these problems.

Concluding remarks

In conclusion, 3D printing of full-scale construction components is still an emerging technology and as an alternative construction method is attracting increasing attention. The main challenge associated with MDM is to develop appropriate material that can be extruded continuously and stacked up over one another without causing any deformation in the bottom bead layers. It is important to perform finite element analysis to simulate both structural loads and material reactive properties for architectural components printed using cementitious, viscous materials to understand its behaviour under loading.

As 3D printing and automation for B&C progresses, it would be ideal to eliminate human involvement necessary for potentially dangerous tasks, such that the risk involve in these dangerous task could be eliminated. With the integration of BIM, it can also help to mitigate some of the key challenges of a construction project such as construction planning and monitoring, effective communication, safety and procurement management. As implementation of 3D printing surge, it is expected that the labour involvement may reduce, as such there might be fewer opportunities for employment on any given project unless traditional construction workers find a way to evolve with this new technology and remain relevant.

While 3D printing can offer many advantages such as creating complex design, time saving and material saving (Zhang & Khoshnevis 2013) the need to abolish conventional methods completely may not be necessary. The future of construction is most likely to be an integrated process that allows organizations to take advantage of both conventional and 3D printing technologies at the same time.

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Reference

Abderrahim, M.; Garcia, E.; Diez R. & Balaguer, C. 2003. A mechatronic security system for construction site, *Journal of Automation in Construction*, 14(4), pp. 460-466.

Aejmelaeus-Lindström, P., Willmann, J., Tibbits, S., Gramazio, F. and Kohler, M., 2016. Jammed architectural structures : towards large-scale reversible construction. *Granular Matter*, 18(2), pp.1–12.

Arayici, Y., Egbu, C. & Coates, P., 2012. Building Information Modelling (Bim) Implementation And Remote Construction Projects : Issues , Challenges , And Critiques. *Journal of Information Technology in Construction*, 17, pp.75–92.

Azhar, S., 2011. Building Information Modeling (BIM): Trends, Benefits, Risks, and Challenges for the AEC Industry. *Leadership and Management in Engineering*, 11(3), pp.241–252.

Bekas, D.G., Tsirka, K., Baltzis, D. and Paipetis, A.S., 2016. Self-healing materials: a review of advances in materials, evaluation, characterization and monitoring techniques. *Composites Part B: Engineering*, 87, pp.92-119.

Biswas, G., Bhattacharya, A. and Bhattacharya, R., 2017. Occupational health status of construction workers: A review. *International Journal of Medical Science and Public Health*, 6(4).

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*, 11(3), pp.209-225.

Brackett, D., Ashcroft, I. and Hague, R., 2011, August. Topology optimization for additive manufacturing. *In Proceedings of the solid freeform fabrication symposium*, Austin, TX, pp. 348-362.

Bryde, D., Broquetas, M. & Volm, J.M., 2013. The project benefits of Building Information

Modelling (BIM). *International Journal of Project Management*, 31(7), pp.971–980.

Buswell, R.A., Soar, R.C., Pendlebury, M., Gibb, A.G., Edum-Fotwe, F.T. and Thorpe, T., 2005. Investigation Of The Potential For Applying Freeform Processes To Construction. *In: Proceedings of the 3rd International Conference on Innovation in Architecture, Engineering and Construction (AEC)*. Rotterdam, The Netherlands, pp. 141–150.

Capua, A., Shapiro, A. & Shoval, S., 2014. SpiderBot: A cable-suspended walking robot. *Mechanism and Machine Theory*, 82, pp.56–70.

Cesaretti, G., Dini, E., De Kestelier, X., Colla, V. and Pambaguian, L., 2014. Building components for an outpost on the Lunar soil by means of a novel 3D printing technology. *Acta Astronautica*, 93, pp.430-450.

Chang, Y. & Shih, S., 2013. BIM-based Computer-Aided Architectural Design. *Computer-Aided Design and Applications*, 10(1), pp.97–109.

Cho, W., Sachs, E. M., Patrikalakis, N. M., Cima, M. J., Liu, H., Serdy, J., Stratton, C.C., 2002. Local Composition Control in Solid Freeform Fabrication. In: *Proceedings of the 2002 NSF Design, Service and Manufacturing Grantees and Research Conference*. San Juan, Puerto Rico.

Chua, C.K. & Leong, K.F., 2014. *3D Printing and Additive Manufacturing: Principles and Applications* 4th Editio., World Scientific Publishing.

Conner, B. P., Manogharan, G. P., Martof, A. N., Rodomsky, L. M., Rodomsky, C. M., Jordan, D. C., & Limperos, J. W., 2014. Making sense of 3-D printing: Creating a map of additive manufacturing products and services. *Additive Manufacturing*, 1–4, 64-76. doi:http://doi.org/10.1016/j.addma.2014.08.005

Craveiro, F., Bártolo, H. & Bártolo, P., 2013. Functionally Graded Structures through Building Manufacturing. *Advanced Materials Research*, 683, pp.775–778.

de Witte, D. 2015. Concrete in an AM process: Freeform concrete processing.. M.Sc. TU Delft, Delft.

Dini, E., 2009. D-SHAPE - The 21st century revolution in building technology has a name. , pp.1–16. Available at: http://www.cadblog.pl/podcasty/luty_2012/d_shape_presentation.pdf [Accessed December 15, 2015].

Duro-Royo, J. Mogas-Soldevila, L. Kayser, M. & Oxman, N., 2015b. Pneumatic Biomaterials Deposition. Available at: http://matter.media.mit.edu/tools/details/pneumatic-biomaterials-deposition#prettyPhoto [Accessed February 2, 2017].

Duro-Royo, J., Mogas-soldevila, L. & Oxman, N., 2015a. Flow-Based Fabrication : An Integrated Computational Workflow for Design and Digital Additive Manufacturing of Multifunctional Heterogeneously Structured Objects. *Computer-Aided Design Journal*, 69, pp.143–154.

Eastman, C.M., Teicholz, P., Sacks, R., Liston, K., 2011. A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors. 2nd ed., Wiley Publishing.

Elmualim, A. & Gilder, J., 2013. BIM : innovation in design management , influence and challenges of implementation. *Architectural Engineering and Design Management*, 10(3–4), pp.183–199.

Garcia, M.J. & Retsin, G., 2015. Design Methods for Large Scale Printing. In *Proceedings of the 33rd International Conference on Education and Research in Computer Aided Architectural Design in Europe*. Vienna, Austria, pp. 331–339.

Gibson, I., Rosen, D.W. & Brent, S., 2010. *Additive Manufacturing Technologies*, New York: Springer.

Gosselin, C., Duballet, R., Roux, P., Gaudillière, N., Dirrenberger, J. and Morel, P., 2016. Large-scale 3D printing of ultra-high performance concrete – a new processing route for architects and builders. *Materials and Design*, 100, pp.102–109. Available at: http://dx.doi.org/10.1016/j.matdes.2016.03.097.

Habert, G. & Agusti-Juan, I., 2016. An Environmental Perspective on Digital Fabrication in Architectural and Construction. In *Pproceedings Of The 21st International Conference On Computer-Aided Architectural Design Research In Asia (CAADRIA)*. pp. 797–806.

Hack, N. & Lauer, W.V., 2014. Mesh-Mould: Robotically Fabricated Spatial Meshes as Reinforced Concrete Formwork. *Architectural Design*, 84(3), pp.44–53.

Huang, S.H., Liu, P., Mokasdar, A. and Hou, L., 2013. Additive manufacturing and its societal impact: a literature review. *The International Journal of Advanced Manufacturing Technology*, 67(5–8), pp.1191–1203.

Hwang, D. & Khoshnevis, B., 2005. An Innovative Construction Process-Contour Crafting. In *22nd International Symposium on Automation and Robotics in Construction ISARC*. pp. 1–6.

Hwang, D., Khoshnevis, B. & Daniel, E., 2004. Concrete Wall Fabrication By Contour Crafting. In *ISARC 2004 21st International Symposium on Automation and Robotics in Construction*. Jeju Island, South Korea.

Jiang, X. & Hojjat, A., 2007. Pseudospectra, MUSIC, and dynamic wavelet neural network for damage dectection of high rise building. *International Journal for Numerical Methods in Engineering*, 71(5), pp.606–629.

Jin, Y.A., He, Y., Fu, J.Z., Gan, W.F. and Lin, Z.W., 2014. Optimization of tool-path generation for material extrusion-based additive manufacturing technology. *Additive Manufacturing*, 1, pp.32-47.

Kading, B. & Straub, J., 2015. Utilizing in-situ resources and 3D printing structures for a manned Mars mission. *Acta Astronautica*, 107, pp.317–326.

Keating, S., Spielberg, N.A., Klein, J. and Oxman, N., 2014. A compound arm approach to digital construction. In *Robotic Fabrication in Architecture, Art and Design* 2014 (pp. 99-110). Springer International Publishing.

Khoshnevis, B., 2004. Automated construction by contour crafting - Related robotics and information technologies. *Automation in Construction*, 13(1), pp.5–19.

Khoshnevis, B., Hwang, D., Yao, K.T. and Yeh, Z., 2006. Mega-scale fabrication by contour crafting. *International Journal of Industrial and Systems Engineering*, 1(3), pp.301-320.

Kittusamy, N.K. & Buchholz, B., 2004. Whole-body vibration and postural stress among operators of construction equipment: A literature review. *Journal of Safety Research*, 35(3), pp.255–261.

Kothman, I. & Faber, N., 2016. How 3D printing technology changes the rules of the game Insights from the construction sector. *Journal of Manufacturing Technology Management*, 27(7), pp.932–943.

Kwon, H., Bukkapatnam, S., Khoshnevis, B. and Saito, J., 2002. Effects of orifice shape in contour crafting of ceramic materials. *Rapid Prototyping Journal*, 8(3), pp.147–160.

Le, T.T., Austin, S.A., Lim, S., Buswell, R.A., Gibb, A.G. and Thorpe, T., 2012. Mix design and fresh properties for high-performance printing concrete. *Materials and Structures*, 45(8), pp.1221–1232. Available at: http://www.springerlink.com/index/10.1617/s11527-012-9828-z.

Lim, S., Buswell, R.A., Le, T.T., Austin, S.A., Gibb, A.G. and Thorpe, T., 2012. Developments in construction-scale additive manufacturing processes. *Automation in Construction*, 21(1), pp.262–268.

Lim, S., Buswell, R.A., Le, T.T., Wackrow, R., Austin, S.A., Gibb, A.G. and Thorpe, T., 2011. Development of a viable concrete printing process. In *Proceedings of the 28th International Symposium on Automation and Robotics in Construction (ISARC2011)*. Jeju Island, South

Korea, pp. 665–670.

Lim, S., Buswell, R.A., Valentine, P.J., Piker, D., Austin, S.A. and De Kestelier, X., 2016. Modelling curved-layered printing paths for fabricating large-scale construction components. *Additive Manufacturing*, 12, pp.216–230. Available at: http://dx.doi.org/10.1016/j.addma.2016.06.004.

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. *CAD Computer Aided Design*, 60, pp.40–49.

Maas, G. & Gassel, F. Van, 2005. The influence of automation and robotics on the performance construction. In *Automation in Construction*. pp. 435–441.

Mahamood, R.M., Akinlabi, E.T., Shukla, M. and Pityana, S., 2012. Functionally Graded Material : An Overview. *World Congress on Engineering*, III, pp.2–6.

Meliá, J.L., Mearns, K., Silva, S.A. and Lima, M.L., 2008. Safety climate responses and the perceived risk of accidents in the construction industry. *Safety Science*, 46(6), pp.949-958.

Ministry of Manpower, 2017. OSHD Annual Report 2015. [online] Singapore, pp.28-35. Available at: http://www.mom.gov.sg/ebook/oshd-ar2015/pdf/OSHD_AR2016_LoRes.pdf [Accessed 26 Apr. 2017].

Nan, C., 2015. A New Machinecraft: A Critical Evaluation of Architectural Robots. In *Computer-Aided Architectural Design Futures. The Next City - New Technologies and the Future of the Built Environment, CAAD Futures 2015, International Conference on Computer-Aided Architectural Design Futures*. Sao Paulo, Brazil, pp. 422–438.

Nerella, V.N., Krause, M., Näther, M. and Mechtcherine, V., 2016. Studying printability of fresh concrete for formwork free Concrete on-site 3D Printing technology (CONPrint3D). In *In Proceeding for the 25th Conference on Rheology of Building Materials*. Regensburg, Germany.

Neville, A.M., 1995. *Properties of Concrete* 4th ed., England, UK: Longman Group Limited.

Oxman, N., Duro-Royo, J., Keating, S., Peters, B. and Tsai, E., 2014. Towards robotic swarm printing. *Architectural Design*, 84(3), pp.108–115.

Panda, B. N., Bahubalendruni, R. M., Biswal, B. B., & Leite, M. 2016. A CAD-based approach for measuring volumetric error in layered manufacturing. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, DOI:10.1177/0954406216634746

Park, J.M., Kwon, D.J., Wang, Z.J. and DeVries, K.L., 2015. Review of self-sensing of damage and interfacial evaluation using electrical resistance measurements in nano / micro carbon materials- reinforced composites. *Advanced Composite Materials*, 24(3), pp.197–219. Available at: http://dx.doi.org/10.1080/09243046.2014.939541.

Perkins, I. & Skitmore, M., 2015. Three-dimensional printing in the construction industry: A review. *International Journal of Construction Management*, 15(1), pp.1–9.

Perrot, A., Rangeard, D. & Pierre, A., 2015. Structural built-up of cement-based materials used for 3D-printing extrusion techniques. *Materials and Structures*.

Petersen, K., Feldt, R., Mujtaba, S. and Mattsson, M., 2008. Systematic Mapping Studies in Software Engineering. *EASE*, 8, pp.68–77.

Senthil Kumaran, D., Ong, S.K., Tan, R.B. and Nee, A.Y.C., 2001. Environmental life cycle cost analysis of products. *Environmental Management and Health*, 12(3), pp.260-276.

Tay, Y.W., Panda, B., Paul, S.C., Tan, M.J., Qian, S.Z., Leong, K.F. and Chua, C.K., 2016. Processing and Properties of Construction Materials for 3D Printing. *Materials Science Forum*, 861, pp.177–181.

Thomas, D.S. and Gilbert, S.W., 2014. Costs and cost effectiveness of additive manufacturing. *NIST Special Publication*, 1176, p.12.

Vaezi, M., Seitz, H. & Yang, S., 2013. A review on 3D micro-additive manufacturing technologies. *The International Journal of Advanced Manufacturing Technology*, 67(5), pp.1721–1754.

van Zijl, G., Paul, S.C. & Tan, M.J., 2016. Properties Of 3d Printable Concrete. In *Proceeding for 2nd International Conference on Progress in Additive Manufacturing (Pro-AM)*. Singapore, pp. 421–426.

Williams, R.L., Albus, J.S. & Bostelman, R. V, 2004. Self-contained automated construction deposition system. *Automation in Construction*, 13, pp.393–407.

Wit, A.J., 2015. The One Day House Intelligent Systems for Adaptive Buildings. In *Association for Education and Research in Computer Aided Architectural Design Europe (ECAADE)*. pp. 1–8.

Wolf, R.J., 2015. *3D printing of concrete structures*. Eindhoven University of Technology, The Netherlands.

Wu, P., Wang, J. & Wang, X., 2016. A critical review of the use of 3-D printing in the construction industry. *Automation in Construction*, 68, pp.21–31. Available at: http://dx.doi.org/10.1016/j.autcon.2016.04.005.

Yoshida, H., Sakai, K. & Igarashi, S., 2015. Architecture-Scale Human-Assisted Additive Manufacturing. *ACM Transactions on Graphics*, 34(4), pp.1–8.

Zavadskas, E.K., 2010. Automation in Construction Automation and robotics in construction : International research and achievements. In *Automation in Construction*. Elsevier B.V., pp. 286–290.

Zegard, T. and Paulino, G.H., 2016. Bridging topology optimization and additive manufacturing. *Structural and Multidisciplinary Optimization*, 53(1), pp.175-19.

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

Zhou, Z., Irizarry, J., and Li, Q. 2013. Applying advanced technology to improve safety management in the construction industry: a literature review. *Construction Management & Economics*, 31(6), pp. 606–622.