X Юбилейна международна научни конференция
„Проектиране и строителство на сгради и съоръжения“, 20-22 септември 2018 г, Варна

X Jubilee International Scientific Conference
„Civil Engineering Design and Construction“ (Science and Practice), Sept. 20-22, 2018, Varna, Bulgaria

ШИРОКОМАЩАБНО ПРИНТИРАНЕ В АРХИТЕКТУРАТА: МОТИВАЦИЯ И ПРЕДИЗВИКАТЕЛСТВА

Орли Талйосеф[1]

LARGE SCALE PRINTING IN ARCHITECTURE: MOTIVATION VS CHALLENGES

Orly Talyosef[1]

Abstract:
Additive manufacturing of concrete (AMoC) also known as 3D printing (3DP) is an advanced manufacturing technology for building and construction (B&C) without any molds. The main advantage of this method, regarding the traditional technique, is creating complex geometries. This automated manufacturing process has been applied successfully to various industrials domains such as aerospace, automobile, medical, jewelry and etc. A more recent application of this AMoC is to improve traditional architecture and building industry. In this process, the drawing made in the CAD software is approximated by triangles and sliced containing the information of each layer that is going to be printed. It causes the slice not to be fully fitted to the model plan. Additionally, there are causes in the mid print process and in the post process that prevents AMoC from replacing traditional building technology. This article, a Qualitative research method, summarizes all Large-scale 3D printing technology methods in Architecture and Building and Construction (A&B&C) Fields as follows: Contour crafting, D-shape and Concrete printing. This paper explores the motivation and challenges of AMoC versus the traditional building technique.

Keywords:
Additive Manufacturing of Concrete (AMoC), 3D Printing (3DP), Concrete Printing, D-Shape, Contour Crafting, Architectural Design, Computer-aided Design (CAD), Building and Construction (B&C), Architecture.

1. INTRODUCTION

Since the 1990s, technologies have been developed to manufacture solid objects through robotized deposition in stone-like materials without molds, on a scale that is relevant to buildings. A variety of deposition strategies, robots, printer heads, and materials have been used [1]. The construction industry continues to have a higher rate of fatality, injury and illness of construction workers. This compels to increase workplace safety [2]. The construction industry has traditionally relied on specifications and two-dimensional (2D) drawings to convey material

[1] Orly Talyosef, PhD student, Department of Architecture and Urban studies, Faculty of Architecture;
Varna Free University „Chernorizets Hrabar“, Varna, Bulgaria / Lecturer Faculty of Architecture, Ariel University Israel,
e-mail: orlyt@ariel.ac.il

properties, performance details, and locational information – using small-scale models to create the object for evaluation as part of the design process. Increasingly, specifications and 2D drawings are being replaced by three-dimensional (3D) modeling in the virtual environment of building information modeling (BIM). An alternative to 3D modeling is the use of advanced 3D solid modeling techniques in combination with digital fabrication methods. In the digital fabrication process, the 3D objects are ‘sliced' and represented as a series of 2D layers, with layer-based methods sequentially adding each layer to build up the desired object. It is the selectivity and control of the material that enables the freedom to build any desired geometry, which is the fundamental advantage of these processes [3]. 3D printing shows its efficiency and benefits in various industrial sectors such as aerospace, automobile and medical. It continues to grow with the addition of new technologies, methods, and applications [2]. This paper will highlight the benefits of 3D printing technology for the B&C industry as well as the many challenges it faces.

1.1. CURRENT existing methods for AM processes in Construction

Over the years there were some entities from different places in the world that explores and develops the 3D printing for B&C. Nowadays; developments are going so fast that any research of existing techniques and examples is out-of-date almost as soon as it is published. Research interest in employing 3DP in the B&C industry has exponentially growth between the years 1997-2016 as shown in Figure 3. That includes journal articles and conferences. From 2009 onwards, articles publications is growing faster that conferences which demonstrates a more comprehensive work in the architecture and construction industry [2].

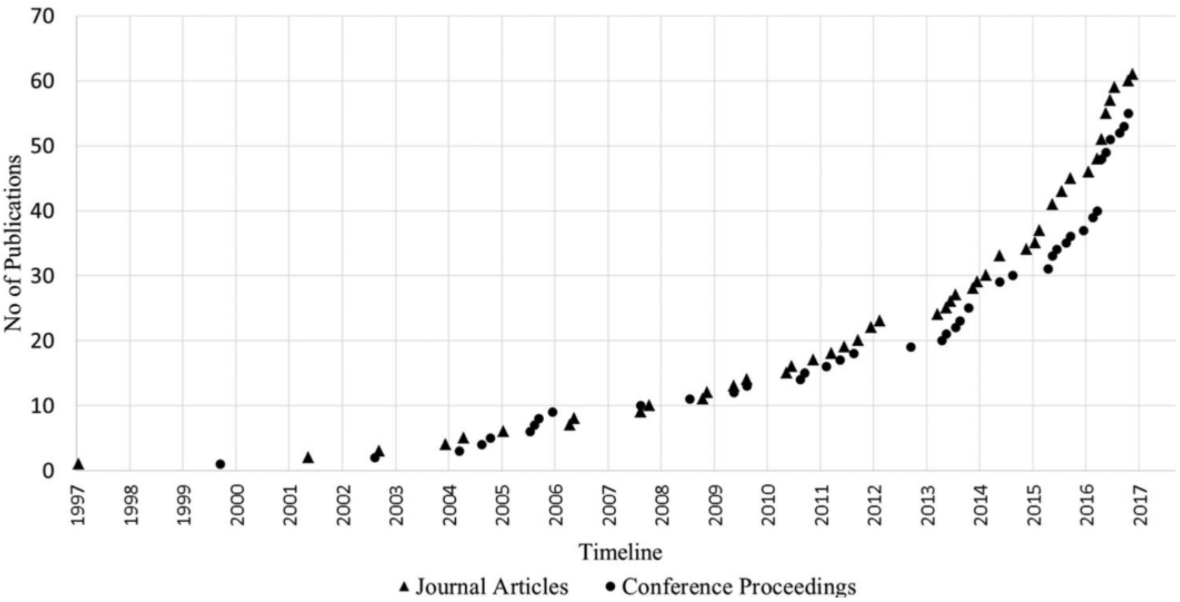

Figure 1. Trends of publication output over the years [2]

Currently, in the B&C field, there are main large-scale processes targeted at construction and architecture in the public domain, namely: Contour crafting developed by Dr. Behrokh Khoshnevis, D-shape developed by Enrico Dini and Concrete printing developed by the Loughborough University. All three methods have proven the successful manufacturing of components with significant size and all are suitable for construction or architectural applications. The deposition head mounting is the frame, robot or crane mounted [4] [5].

Existing research and practice related to AM processes in Construction.

	Contour Crafting	Concrete Printing	D-Shape
Process	Extrusion	Extrusion	3D Printing
Use of mould	*Yes* (Becomes a part of component)	*No*	*No*
Build material	• Mortar mixture for mould • Cementitious material for build	In-house Printable Concrete	Granular material (sand *I* stone powder)
Binder	None (Wet material extrusion and backfilling)	None (Wet material extrusion)	Chorline-based liquid
Nozzle diameter	15 mm	9–20 mm	0.15 mm
Nozzle number	1	1	6 300
Layer thickness	13 mm [21]	6– 25 mm	4–6 mm
Reinforcement	*Yes*	*Yes*	*No*
Mechanical properties	*Tested* with zero degree (0°) of layer orientation, which means the force was given *from the top* of the printed surface		
Compressive strength	unknown	100 110 MPa	235 242 MPa
Flexural strength	unknown	12–13 MPa	14–19 MPa
Print size	>1 m dimension	>1 m dimension	>1 md dimension
Pre *I* Post processing	• Reinforcement *per* 125 mm vertically • Backfill the mould with a cementitious material per 125 mm height	• Reinforcement after printing	• Compression of the powder for next layer by a roller with light pressure prior to the deposition • Removal of unused material

Figure 2. Existing research and practice related to AM process in Construction [5]

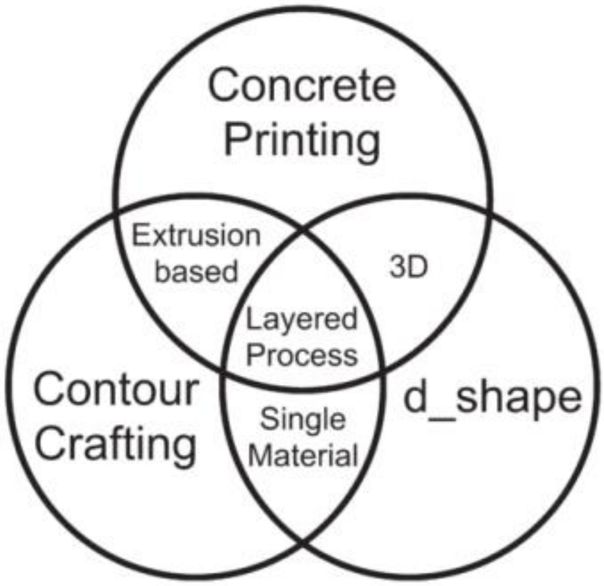

Figure 3. Similarities between the processes [5]

2. MOTIVATION AND CHALLENGES OF 3D PRINTING IN THE ARCHITECTURE AND CONSTRUCTION INDUSTRY

2.1. MOTIVATION

Three- dimension printing has several significant advantages in the B&C industry as well as major challenges to deal with over traditional construction methods. There is growth in the researchers' group and in articles that are trying to solve those challenges, but still, there is a lot to explore in the pre-process, mid print and the post process stages.

2.1.1. DESIGN freeform architectural design

3DP offers the possibility of creating, in a short timeframe, a complex 3D objects with fine details, from different materials without molds or milling. that are impossible to be obtained through any other existing technology [6]. Architects and engineers have limited their designs to standardized shapes and parts to smooth or reduce the construction time. When a unique part is needed for a project, it takes more than just the design to make it a finished product [7].

2.1.2. CUSTOMIZATION

3D printing is very economical in the manufacturing of precisely customized parts on demand [8]. The benefits of being able to print elements on demand eliminate the need for inventory [7].

2.1.3. WORKER safety

The construction industry has started looking to mitigate current challenges such as worker safety in extreme environments, decreases in skilled workforce availability, and a waste of materials [7]. The labor involved, particularly for in-Situ cast concrete and the placement of reinforcement still require physically demanding labor, particularly when bespoke geometries needed. This results in personal health issues of construction workers that should be avoided as much as possible, particularly with an aging workforce as in many developed countries [1]. A solution used to address such issues has been the off-site fabrication, where parts and assemblies are delivered to and assembled on-site, reducing the amount of on-site labor [7].

2.1.3. SKILLED workforce safety

Recruit a workforce with the necessary skills (e.g., experienced carpenters, heavy equipment operators, welders, and fabricators) is not an easy task for contractors. The use of AM in construction should lower the demand for skilled craft while at the same time opening new opportunities for jobs with different skill sets [7].

2.1.4. SAVING time and materials

In the field of construction virtually every wall, floor, panel, partition, structure, and facade is unique in dimension, which means either standard-sized materials are cut down to fit, or bespoke molds are created to form each component. There is a certain cost-based opportunity to save time and materials by reducing waste and the need for formwork making [5]. Building with these techniques could significantly accelerate the speed of finishing construction projects and reduces cost and materials [9].

2.1.5. GREEN environment

Another critical advantage of creating objects using 3D printing technology instead of traditional manufacturing methods is the waste reduction. As the construction material is added layer after layer, the waste is almost zero, and during the production, it is used solely the material needed for obtaining the final object. On the other hand, in the traditional manufacturing processes, based on subtractive techniques, the manufactured product is made through cutting or drilling an initial object, thus leading to a substantial loss of material [10].

2.1.6. OPERATING cost

Moreover, since the additive manufacturing is a computer-controlled technique and no formwork is required, it reduces the necessary amount of human interaction and requires a low level of expertise for the operator. Therefore, the costs of operating these 3D printers are significantly lower in comparison to the traditional way of manufacturing [7] [11] [12].

2.1.7. REMOTE printing

The advantages of this technology are not limited only to manufacturers, but also to end-users. The customers also have the possibility of printing items in remote locations taking into account the fact the Internet is nowadays widespread and in some countries is even a legal right of the citizen [12].

2.1.8. OUTSOURCING of design/manufacturing

A significant advantage of 3-D printing is the separation of product design from manufacturing capabilities. Since design and manufacturing can be easily outsourced to 3D printing, designers can contract with firms to produce, ship, and collect proceeds for goods based on their models. Alternatively, a consumer can download a CAD software design for a replacement part online and then download and print the part on his/her 3-D printer [13].

2.2. CHALLENGES

Notwithstanding the potential benefits, 3D printing in B&C faces several challenges as follows:

2.2.1. SHAPE optimization

Optimization of the design space is the ability to fill the interior part of the object in practically infinite ways. The design space is any area of the model that can include the boundaries as well as the interior of the model. Optimizing the design space is a serious problem. The goal of this process is to find the best way to fill in the design space with material that optimizes specific design parameters including strength, mass, and volume. The two approaches that are commonly used to find the best allocation of the material area are **a.** ‘Cellular structures,' that fills the design space of the model with geometric shapes such as honeycombs, lattices, and other repeatable shape elements. The number of structures cells that fill a space could be in the thousands or even tens of thousands. **b.** ‘Topological optimization’(TO) is a mathematical approach, lays out the material in the design area, based on a set of physical variables and constraints of the design space (e.g., loads, boundary conditions, mass and volume budget, material drying time). If the topology analysis is inaccurate, the optimization may not work correctly [14] [15]. XtreeE optimized an element by inserting voids where a material is not needed for structural purposes [7].

2.2.2. STL slicing

The STL file was created in 1987 by 3D Systems Inc. It is also called Standard Tessellation Language. The 3D virtual model is being cut on the horizontal plane. The most popular method of slicing is uniform slicing, usually called 2.5D contours, which means that each layer has the same thickness regardless the geometry. This method of slicing created two major challenges that appear on curved geometry: staircase effect caused by layer thickness and containment issue caused by the tessellation process on the horizontal plane that makes some of the triangles in or out the geometry- the smaller the triangles, the closer to reality. These challenges are the reason for poor surface quality as well as inaccuracy [14] [16]. To reduce this inaccuracy, the technique for a feature that has a small radius in relation to the dimension of the part is to create STL files separately and to combine them later. The dimension in z-direction should be designed to have a multiple of the layer thickness value [16]. Lim et al. examined new algorithms by Grasshopper – a plugin of Rhinoceros®. The method was evaluated with the 3D Concrete Printing process developed at Loughborough University. The designer can change a layer thickness and printing path, after the layers and paths are created, according to the boundary conditions and geometric shape by simply adjusting parameters interactively. Because its path generator does not rely on a single mathematical algorithm or solution, it has few limitations in terms of slicing and generating printing paths. The results were: better surface quality, shorter printing time and higher surface strengths [17].

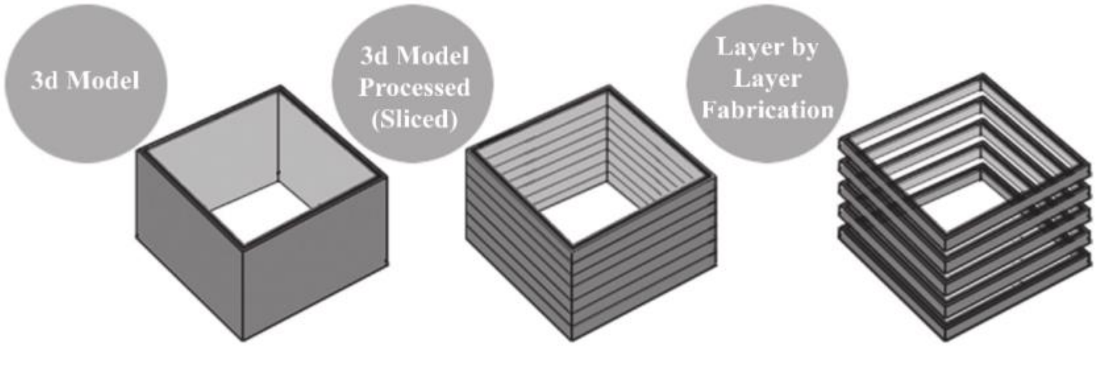

Figure 3. Additive manufacturing (AM) process [18]

2.2.3. QUALITY and reliability

To assure quality and reliability of printed materials, the primary objective is to minimize the gap between a CAD model and the corresponding manufactured part [19]. For that, real-time monitoring of environmental, material, and geometrical properties such as temperature, cooling rate, viscosity, defects, and dimensions of the material should be made. Further work is needed to correlate these factors, as measured during printing, to expected mechanical properties and performance of the finished product. Without sufficient data, it is unclear how imperfections or variations due to inaccuracy during construction would affect the performance of structures produced using AM [7].

2.2.4. PRE-PROCESSING and post-processing

The model in the CAD software must be pre-processed before being passed to the printer as a series of instructions for how to construct the part. A CAD model can be approximated using planar triangles via tessellation. There may be accuracy issues in the final part, especially in curved surfaces and errors via redundant triangles, missing geometry, and misaligned facets. Once the part is printed, it requires post-processing actions as to remove supports, improve surface quality (grinding or plastering), or finalize specific features leading to a further increase in the post-processing costs [20] [14] [21] [2].

2.2.5. SCALING effects

The objective is a scaling-up of a desktop 3D printer to the size of a building site. At this time such techniques are not sufficiently developed for industrial application but have succeeded in producing wall elements under laboratory conditions [22]. Recent developments in scaling up a process to create complex construction scale components were presented and discussed the development of the approach and preliminary components have been manufactured with different nozzle diameters [23].

2.2.6. THIXOTROPY - behavior of material

Thixotropy defined as a decrease in viscosity when shear is applied. The material thixotropic is essential since, in 3DCP, the material needs to be pumped and at the same time gain strength to carry the load from the next layer [8]. During the flow of material deposition, it may happen to have ‘Over-printing’ or ‘Under-printing.' ‘Over-printing' is when too much material is deposited at a specific point, leading to 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 [2]. Another issue is hydration of concrete with time. The hardening properties of concrete make it hard to extrude the concrete. Once the bulk amount of concrete is ready for 3D printing, in the beginning, the printing quality is considered to be good, but with time hydration process accelerates and matrix becomes harder and hard to pump (changing plastic to setting state). Over time, some water may also be lost due to evaporation from the mix leading to reduced printing quality. As a result, concrete layers and interfaces of more inferior quality might have been created in the upper layers than the bottom layers that were printed much earlier. Apparently, this phenomenon is valid when the object is larger and printing time is longer [11].

2.2.7. MULTIPLE materials: Modeling and printing stages

3D printers can use a variety of materials for homogenous parts. The two significant obstacles to printing with multiple materials are the modeling and the manufacturing stages. There are suggestions on how to model a heterogeneous part, but each method has its benefits and problems. One of the solutions is to model with Voxels, but the main disadvantage of that is the accuracy of model tessellation resulting from Voxel resolution.

Printing with multiple materials can offer many complications that need to be accounted for in the modeling and manufacturing. The more complicated the data for printing is, the more complicated the processing becomes. Even if the printer can print with multiple materials, there is need to assure that all the materials react well [14].

2.2.8. FLAT-LAYERED printing Vs Curved-layered printing

There are two methods of AM printing: Flat-layered printing and Curved-layered printing. Flat-layered printing is a typical AM process method that prints on 2D plane layer-by-layer to the desired volume. To achieve desired accuracy and resolution, particularly on curved surfaces, more layers are required within the same height. This cause more time-consuming, anisotropy property and staircase effect on the surface. Curved-layered printing is printed on a non-planar layer which means the printing nozzle should be positioned perpendicular to the target surface, regardless of the degree of curvature. This process provides much less stair-effect, It avoids stair-effect at least for one direction [17].

2.2.9. PRINTED object properties

Objects produced with additive manufacturing may have the same geometries as traditionally manufactured objects, but they typically have different material properties. For example, metal parts formed by sintering have a different microstructure than parts milled from metal bulk [24]. Other differences may emerge from flaws in the additive process: Stress concentrations often exist at the junction of two layers. There may be voids between layers. Layers may not cure uniformly. The bottom line is that although it is now easy to print out a copy of a turbine blade, printing a blade to look exactly like the real machined artifact does not guarantee its functionality in operation [25]. Another point to be the issue is getting sufficient robustness and ductility for structural applications. One approach is the concrete bench presented in Lim et al. (2012) has hollow sections over the height of the object. Post-tensioning prestress bars are fed through them after printing. This strategy is also commonly applied in a variety of concrete structures and introduces stiffness and tensile capacity. Another approach is developing a fiber-reinforced printable concrete with sufficient ductility and tensile strength [1].

2.2.10. ANISOTROPY

One of the main disadvantages of 3DP 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 evenly distributed in all directions. Anisotropy may occur both in the bulk material and as a consequence of interface properties of the different interfaces. The extent of anisotropy is yet unknown. The reasons that can lead to this are laying layers of concrete on one on another while during the process are given concrete layers with different physical properties resulting from the printing time gap between the layers. Besides, there are differences in the conditions between the inner and outer sides of the printed wall. There is a difference that results from height differences in the printing base, changes resulting from different angles of interfaces between different layers, changes resulting from printing curves. It recognizes that in 3D printing, design, material, process, and product are all strongly interdependent. In 3DCP, this interdependency is even more pronounced for two reasons. Firstly, the slow setting reaction in the printed concrete results strong interaction with the applied print parameters and strategy such as print speed, pump pressure, filament stacking, etc. Secondly, the concrete itself is not a single fixed material but can have a wide range of compositions that may be more or less suitable to the printing process and the required end product performance properties. Thus, a print strategy cannot be chosen independently from design, material, or (desired) end product considerations. The design of a product influences the end product properties, or the process and material parameters have to be adjusted to avoid this [1] [2]. Some researchers explored the directional properties of 3D printed concrete with the addition of reinforcement, like nanostructured and short Glass fibers, to improve its mechanical and wear resistance properties to unveil anisotropic property of printing process. There have been improvements, but still, a lot of development has to be done to reduce anisotropic nature of the 3DCP process [26]. Since the final product is constructed layer-by-layer, the material compatibility is higher in the horizontal direction compared with the vertical direction. The tensile strength in the vertical direction is related to the bond strength between the successive layers. The layered concrete may create weak joints and reduce the load bearing capacity under compressive, tensile and flexural action that requires stress transfer across or along these joints [11]. Obtaining sufficient consistency in quality for different designs, printed from different material badges under varying conditions, still needs to be proven. It is likely this will first require improvement of the existing 3DCP facilities and development of the understanding of the parameters that influence the final quality. Also, data will need to be collected for 3D printed concrete on some common characteristics, such as shrinkage and creep, to compare the printed material to the concrete commonly applied. Furthermore, connection methods need to be developed to join printed elements together [1].

2.2.11. SURFACE finish

One of the most prominent limitations is the issue of surface finish. The primary contributing factor to poor surface finish in AM processes is the stair-stepping effect. It occurs because of the geometric approximation of curved surface profile using layers of uniform thickness [10]. To reduce the stair-stepping effect, reducing layer thickness is proposed but reducing the layer thickness will adversely affect the speed of the process as well as the properties of the part produced[27]. To address this issue, Brajlih et al. developed a method for measuring achievable speed and accuracy of AM technology. This tool is useful in comparing achievable speed and level of accuracy from any AM machine but still not much achieved [28].

2.2.12. PROCESS and material based issues

Printing process, as well as materials, offers their challenges for 3D printing. There is a need for maintenance of the 3D printer as well as the materials. Otherwise, it may produce a mistaken geometry of the part.

2.2.12. PROCESS based issues

The printer head that pushes material out through the nozzle is sensitive to fillings and can affect the mid printing process. Because the ink heads have a fixed size, the part resolution and construction time are directly affected by the nozzle diameter [14].

2.2.13. MATERIAL based issues

Materials have to be stored carefully. Solid materials and even powders have to be stored in low humidity terms. Materials also have a shelf life. After expiry date of material, the 3D printing quality is not assured [14].

2.2.14. CO_2 footprint

When we see and feel the changes resulting from global warming, greenhouse gases emission into the atmosphere is a topic to consider. Concrete is the most used for building for his properties- strong, cheap, durable, fire resistant, availability in most countries and can be applied in any shape. However, the production of the cement includes burning of slag in the kiln and therefore concrete production it’s an energetic process that causes significant global CO_2 pollution (about 5%) [1].

3. DISCUSSION

3D printing, also called digital fabrication, has been existence for over 30 years and after the expiration of the patent. 3D printing in the B&C field is opening new manufacturing possibilities and unique capabilities. The main advantage of AMoC is creating intricate shapes that cannot be produced in the traditional construction method. Architects can achieve more freedom to create intricate designs. Topology optimization allows architects and engineers to rethink their design based on added functionality. The buildings are designed and built by computer. Sophisticated forms can be produced without affecting the complexity and productivity during the automated construction process. However, this technology is still an emerging technology that need more research. To make 3D printing technology to be used and be popular in the B&C industry, it requires further advancements in research including shape optimization, quality and reliability and anisotropy development research. Furthermore, it needs more accuracy of the printing product to the model and printer-work autonomously and also surface finish improvement, repeatability and speed increase. Beside this, worker-safety is a significant factor to take into account. The construction industry continues to have a higher rate of fatality, injury, and illness rather than any other sectors and therefore needs to deprive from the worker to work in a potentially dangerous task. 3D printing has the potential to revolutionize the construction industry. It requires from Architects, engineers and builders in the construction industry to be ready to innovate and to adopt new construction methods. 3D printing technology for B&C can solve all the challenges facing today, but still, mentioned issues above need to be resolved before AM can compete with the traditional method.

REFERENCES

[1] F. Bos, R. Wolfs, Z. Ahmed, and T. Salet, “Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing,” *Virtual Phys. Prototyp.*, vol. 2759, no. October, pp. 1–17, 2016.

[2] Y. W. D. Tay, B. Panda, S. C. Paul, N. A. Noor Mohamed, M. J. Tan, and K. F. Leong, “3D printing trends in building and construction industry: a review,” *Virtual Phys. Prototyp.*, vol. 12, no. 3, pp. 261–276, 2017.

[3] R. A. Buswell, R. C. Soar, A. G. F. Gibb, and A. Thorpe, “Freeform Construction: Mega-scale Rapid Manufacturing for construction,” *Autom. Constr.*, 2007.

[4] M. A. Evans and R. Ian Campbell, “A comparative evaluation of industrial design models produced using rapid prototyping and workshop-based fabrication techniques,” *Rapid Prototyp. J.*, vol. 9, no. 5, pp. 344–351, Dec. 2003.

[5] S. Lim, R. A. Buswell, T. T. Le, S. A. Austin, A. G. F. Gibb, and T. Thorpe, “Developments in construction-scale additive manufacturing processes,” *Autom. Constr.*, vol. 21, no. 1, pp. 262–268, 2012.

[6] A. Kazemian, X. Yuan, E. Cochran, and B. Khoshnevis, “Cementitious materials for construction-scale 3D printing: Laboratory testing of fresh printing mixture,” *Constr. Build. Mater.*, vol. 145, pp. 639–647, 2017.

[7] D. D. Camacho *et al.*, “Applications of additive manufacturing in the construction industry – A forward-looking review,” *Autom. Constr.*, vol. 89, no. October 2017, pp. 110–119, 2018.

[8] S. C. Paul, Y. W. D. Tay, B. Panda, and M. J. Tan, “Fresh and hardened properties of 3D printable cementitious materials for building and construction,” *Arch. Civ. Mech. Eng.*, vol. 18, no. 1, pp. 311–319, 2018.

[9] Z. Malaeb, H. Hachem, A. Tourbah, T. Maalouf, N. El Zarwi, and F. Hamzeh, “3D Concrete Printing: Machine and Mix Design,” *Int. J. Civ. Eng. Technol.*, vol. 6, no. April, pp. 14–22, 2015.

[10] D. Dimitrov, K. Schreve, and N. De Beer, “Advances in three dimensional printing - state of the art and future perspectives,” *Rapid Prototyp. J.*, vol. 12, no. 3, pp. 136–147, 2006.

[11] S. Rahman, T. Molyneaux, and I. Patnaikuni, “Ultra High Performance Concrete (UHPC): applications and research,” *Aust. J. Civ. Eng.*, vol. 8353, no. August, pp. 12–20, 2004.

[12] Bassoli E Gatto A Iuliano L Grazia Violante M, "3D printing technique applied to rapid casting," *Rapid Prototyp. J.*, vol. 13, no. 3, pp. 148–155, 2007.
[13] M. Hlavn, "3-D Printing: The Next Industrial Revolution," *Appl. Des.*, no. March, pp. 22–23, 2014.
[14] W. Oropallo and L. A. Piegl, "Ten challenges in 3D printing," *Eng. Comput.*, vol. 32, no. 1, pp. 135–148, 2016.
[15] J. Robbins, S. J. Owen, B. W. Clark, and T. E. Voth, "An efficient and scalable approach for generating topologically optimized cellular structures for additive manufacturing," *Addit. Manuf.*, vol. 12, pp. 296–304, 2016.
[16] K. V. Wong and A. Hernandez, "A Review of Additive Manufacturing," *ISRN Mech. Eng.*, vol. 2012, pp. 1–10, 2012.
[17] S. Lim, R. A. Buswell, P. J. Valentine, D. Piker, S. A. Austin, and X. De Kestelier, "Modelling curved-layered printing paths for fabricating large-scale construction components," *Addit. Manuf.*, vol. 12, pp. 216–230, 2016.
[18] B. Zareiyan and B. Khoshnevis, "Effects of interlocking on interlayer adhesion and strength of structures in 3D printing of concrete," *Autom. Constr.*, vol. 83, no. July, pp. 212–221, 2017.
[19] D. I. Wimpenny, P. M. Pandey, and L. J. Kumar, *Advances in 3D Printing & Additive Manufacturing Technologies*. 2017.
[20] I. Gibson, D. W. Rosen, and B. Stucker, "Additive manufacturing technologies: Rapid prototyping to direct digital manufacturing," *Addit. Manuf. Technol. Rapid Prototyp. to Direct Digit. Manuf.*, pp. 1–459, 2010.
[21] P. Delfs, M. T̈ows, and H. J. Schmid, "Optimized build orientation of additive manufactured parts for improved surface quality and build time," *Addit. Manuf.*, vol. 12, pp. 314–320, 2016.
[22] A. Perrot, D. Rangeard, and A. Pierre, "Structural built-up of cement-based materials used for 3D-printing extrusion techniques," *Mater. Struct.*, pp. 1213–1220, 2016.
[23] S. S. Uppala and M. R. Tadikamalla, "A Review on 3D Printing of Concrete-The Future of Sustainable Construction," *i-Manager's J. Civ. Eng.*, vol. 7, no. 3, pp. 49–62, 2017.
[24] K. T. C. W, "Rethinking Additive Manufacturing and Intellectual Property Protection," *Res. Manag.*, vol. 57, no. 5, pp. 35–42, 2014.
[25] Cohen, W.M., Nelson, R.R. and Walsh, J.P., "Protecting Their In tellectual Assets: Appropriability Conditions and Why U.S. Manufacturing Firms Patent (or Not)," *Work. Pap. 7552, Natl. Bur. Econ. Res.*, 2000.
[26] B. Panda, S. Chandra Paul, and M. Jen Tan, "Anisotropic mechanical performance of 3D printed fiber reinforced sustainable construction material," *Mater. Lett.*, vol. 209, pp. 146–149, 2017.
[27] D. S. A. C, "Description and Modeling of the Additive Manufacturing Technology for Aerodynamic Coefficients Measurement," *Strojniški Vestn. – J. Mech. Eng.*, vol. 58, no. 2, pp. 125–133, 2012.
[28] B. T. T. T. D. I. V. B. H. M. et. Al., "Possibilities of Using Three-Dimensional Optical Scanning in Complex Geometrical Inspection," *Strojniški Vestn. – J. Mech. Eng.*, vol. 57, no. 11, pp. 826–833, 2011.