

# 3D Printing Architectural Freeform Elements: Challenges and Opportunities in Manufacturing for Industry 4.0

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## Abstract –

Three-dimensional (3D) printing, as one of the additive manufacturing (AM) technologies, is transforming the design and manufacture of products and components across a variety of disciplines, however, architectural design and the construction industry have only recently begun to adopt these technologies for construction purposes. AM is considered one of the core technological advances in the paradigm shift to Industry 4.0 (the fourth industrial revolution). This term used to describe digitization and automation of the manufacturing environment and is widely recognized as a disruptive technology that could transform architectural design and the construction industry. The potential advantages of 3D printing in the construction sector are significant. They include not only improved environmental and financial resource efficiencies, but also, the capacity to produce complex customized designs for aesthetic and structural applications.

As the cost of building houses continues to rise, it is crucial to find innovative ways to build houses efficiently and cost effectively. The earliest records of 3D printing date back to the 1980's and many industries—from manufacturing to medicine—were early adopters of the technologies resulting in many significant technological advances in those sectors from organ printing to aircraft fabrication. Currently available 3D printing technologies can be adopted for building construction and this paper discusses the applications, advantages, limitations and future directions of 3D printing as a viable solution for affordable house construction with a focus on printing architectural freeform elements.

3D printing offers a new and innovative method of house construction. For this study, an analytical, as well as a numerical model were specifically designed for 3D printing. Previous studies conducted found that the construction of a 3D printed truss-like roof in a cement mixture with high-density polyethylene

(HDPE), spanning the entire structure, was structurally feasible in the absence of steel reinforcements. These results led us to investigate the feasibility of 3D printing an entire house without the use of reinforcements. Investigations were also performed on comparing flat-roof and arch-roof structures and found that whilst maximum tensile stresses within flat-roof would cause the concrete truss structure to fail, the HDPE cement mix in an arch-roof structure had reduced the maximum tensile stresses to an acceptable range to withstand loadings. At the time of writing this paper, several 3D printing techniques could be adopted for the purposes of 3D printing an entire house, and the team believes that future adaptations of existing technologies and printing materials could eliminate the current limitations of 3D printing and become common practice in house construction.

## Keywords –

3D printing; design; architectural freeform elements; construction, Fusion 360 Software; G-code; human-interface, Industry 4.0.

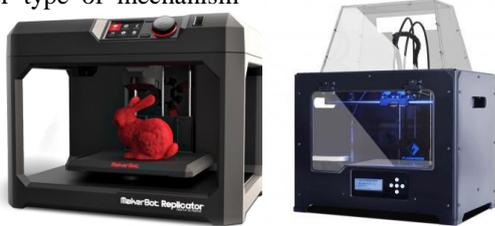
## 1 Introduction

There is a growing trend in architectural design and the construction industry to adopt Industry 4.0 and utilize additive manufacturing processes for building construction. Applying 3D printing in design and construction provides potential advantages as infinite forms and shapes, including large sized elements, can be created in-situ on congested or difficult to access construction sites.

The terms additive manufacturing and 3D printing both refer to the process of creating an object by sequentially adding build material in successive cross sections, or layer upon layer deposition. 3D printing also includes the hardware, machine control systems and software as well as the peripheral accessories which may

be required for producing objects during a building cycle [1]. The blueprint for the form is from a digitally constructed model created in 3D modelling software such as Fusion 360, Rhinoceros, Revit or a multitude of other 3D modelling software packages.

3D printing is the fabrication of objects through the deposition of a material using a 3D printing technology, or type of mechanism



with a print head and nozzle [1]. AM technologies include gantry systems, suspended platforms, and mobile rotating manipulators with an extension arm. The gantry system is the most commonly adopted technology by manufacturers of model size fused deposition

modelling (FDM) 3D printers such as MakerBot and FlashForge.

Whilst this system works effectively in laboratories, for in situ construction scale 3D printing, gantry systems have limitations akin to those of pre-fabricated houses in that they require transportation and installation of heavy infrastructure, which, in turn also can limit the size of the build envelope. Contour Crafting completed a proof of concept at full house scale 3D print in the United States in 2001.

The term “cable-suspended platform” is used for 3D printing technologies that consists of an end-effector that is manipulated by automated motors via multiple cables attached to a rigid frame. The flexibility within well-engineered frame design means that the cable-suspended platform frees up the size of the build envelope and can be constructed from light-weight materials that are assembled on site. Being lightweight and delivered in parts this system can be less expensive to transport to site but requires expertise for assembly.

Mobile rotating manipulators comprise of a rotating arm on a central base. Apis Cor in Russia was the first company to develop a mobile 3D printer for the construction industry and claims to have successfully printed a 37m<sup>2</sup> house on site in 24 hours at a cost of US\$10,134. The Apis Cor has a reach of 8500mm from a central manipulator with 360° rotation and a maximum height of 3100mm. Due to its large build envelope and low cost of materials, the mobile rotating manipulator system in the form of the Potterbot Scara (Selective Compliance Assembly Robot Arm) XLS-2 clay printer

was selected as the most appropriate 3D printing technology for conducting laboratory-based experiments for this study.

Previous studies have generally looked at 3D printing specific geometrical shapes such as wall segments, cubes and vertically extruded curves. Many recently completed 3D printed projects—such as Contour Crafting in the United States, Apis Cor in Russia, and Winsun in China—have provided evidence that the 3D printing of houses can be realised at various scales including 3D printing simple geometry houses at full scale. However, an under developed area in 3D printing in construction is the production of architectural freeform elements (AFE) including extreme slopes, angles and complex curves. This paper aims to create several AFEs and discusses the challenges of creating these models in a laboratory. The paper aims to identify different factors of attainable AFEs from a practical perspective. Many previous studies and built full sized projects focused on producing simple vertically extruded geometries but further investigation is required to find out what are the possible challenges and opportunities of creating AFEs at different scales and sizes.

Researchers in the field of aerospace and manufacturing have demonstrated that 3D printing can reduce costs, but limited investigations have been undertaken to support the assumption that savings will also apply in the construction industry [2]. However, it is still appropriate to hypothesize that utilizing 3D printing can reduce costs for aesthetic and structural applications in the construction industry. Another motive to apply 3D printing technology within the construction Industry is the potential for increased safety. The construction industry has been shown to have a higher rate of fatality, injury and illness than any other sector [3]. So whilst traditional construction may appear straightforward from two-dimensional (2D) drawings, building any kind of freeform or complex curvature structure requires formwork and much skilled labor. The proposed solution and a focus of this study is to minimize and simplify the level of human-interface and human-machine or robot interaction to enable 3D printing technologies to become safe, cost effective and accessible tools in the construction industry.

## 2 Research Method and Data

This study is a laboratory-based investigation. We designed nine architectural freeform models and scaled them to be fabricated as models in a laboratory. A total of 56 samples were created in the lab, and overall running time of printing was approximately 30 hours. A 3D Potterbot XLS-2 (Scara) clay printer (see Fig.1) was used for the experiments as it is able to print large models in continuous flow system of layer deposition.

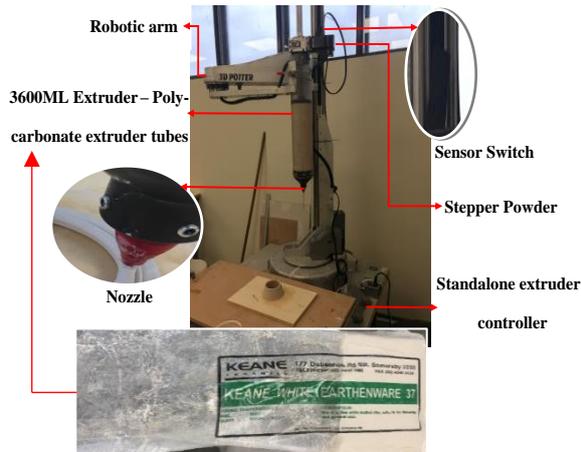


Figure 1. 3D potterbot SLX-2 (Scara) using clay for lab experiments.

The 3D potterbot SLX-2 (Scara) in its seventh series of development has evolved from the previous syringe extrusion method to a mechanical screw system. Earlier Potterbot technologies therefore required a clay and water mix which meant prints could not handle otherwise normal overhangs and did not have good success with achieving significant height.

The material used for this study is clay with no water added, which is suitable for a range of objects from very small to large, even hand applications. The study found that after the initial investment cost of the Potterbot equipment, this technology and material combination can be an efficient and inexpensive option for education and research testing.

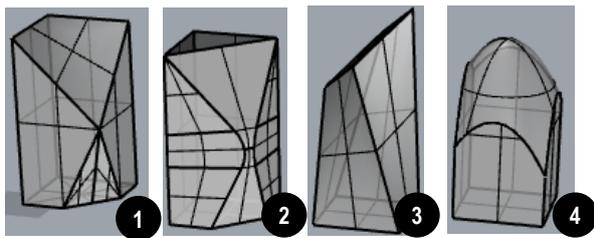


Figure 2. Selected AFE designed models of 4 to 7 for experimentations

Figure 3 shows four models, namely column (M4), column radian (M5), column slope (M6), and column dome (M7). Other models from M1 to M9 are shown in Figure 7. These models can be classified into two groups in terms of design: i) basic models ii) complex or curvature models (e.g. M4 to M7). The software used for these models are Fusion 360 and Simplify3D, which are recommended as compatible programs with the 3D printer Potterbot (XLS-2 Scara robot, 2018).

Models can be designed in any 3D modelling

software and saved as STL files which are then imported into Simplify3D for layer slicing, making them ready to print. The slicing process translates 3D models into instructions the printer understands by generating the G-code programming language, the required numerical code (NC) for motion control of the Potterbot. Any changes to scale or size of the object can be made in Simplify3D software before generating the G-code.

### 3 Experimentations and Failure Modes

Studies were conducted to verify the accuracy of the 3D printed output compared with the digitally produced model. The 30-degree column models were created on Fusion 360 modelling software (see Fig.1). The build envelope dimensions designed for the columns are 100mm x100mm x 120mm.

Table 1. A summary of software used evaluation.

Advantage	Limitations
<b>Fusion 360</b>	
(i) Cloud enabled collaboration platform can create a variety of printable models including organic/complex models more naturally using both NURBS or T-Splines; (ii) Capacity to import models created on other software like Rhino or Revit and then edit specific sections; (iii) Capacity to export as STL file format which can be read directly by 3D slicing printing software like Cura and Simplify3D.	(i) Designing a building model has limitations because Fusion 360 is more suitable for smaller objects (ii) It is relatively new software platform with kinks and issues but is constantly being updated and improved;
<b>Simplify3D</b>	
(i) Compatible with hundreds of different 3D printers; (ii) Can provide a pre-print simulation of model printing actions; (iii) Controls and communicates with the printer.	(i) Some aspects of 3D printer XLS-2 Scara robot motion are not possible to control / predict such as the start point of the extruder for a print; (ii) No free version of Simplify3D is available.

According to all the printed output dimension data, the 20-degree column physical model is the most accurate production of the designed model measuring 99mm x 97cm x120mm. This was more accurate than the 0-degree column output. The models with the most serious deformations are the 30-degree column and 45-degree column. Another factor for future analysis is the impact of increased human presence in proximity to the machine as the models with the most serious deformations correlated with an increase in the number of people present in the lab and in close proximity to the machine, at the time of print.

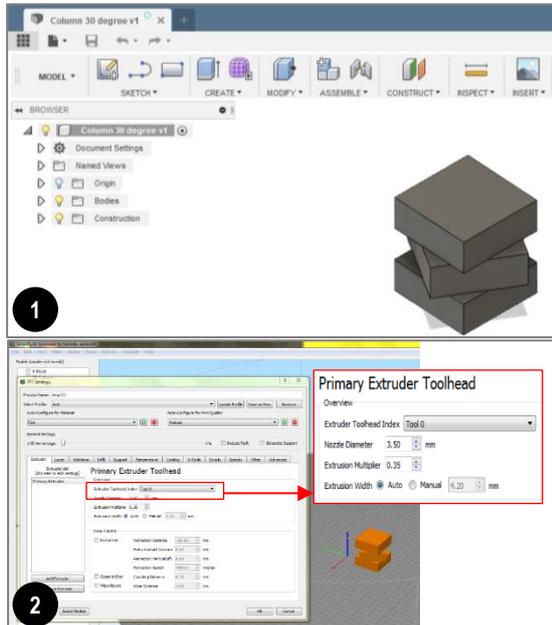


Figure 3. Processing the file in different programs: (1) Fusion 360; (2) Simplify3D with 30-degree column.

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; G-Code generated by Simplify3D(R) Version 4.0.1
; Dec 5, 2018 at 10:56:58 AM
; Settings Summary
; processName,Potterbot Final
; applyToModels,30 Column
; profileName,Potterbot Final 3mm
; profileVersion,2018-11-07 09:55:04
; baseProfile,Default
; printMaterial,PLA
; printQuality,Medium
; printExtruders,
; extruderName,Primary Extruder
; extruderToolheadNumber,0
; extruderDiameter,3.5
; extruderAutoWidth,1
; extruderWidth,4.2
; extrusionMultiplier,0.35
; extruderUseRetract,0
; extruderRetractionDistance,150
; extruderExtraRestartDistance,0
; extruderRetractionZLift,0
; extruderRetractionSpeed,5400
    
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Figure 4. A sample of G-code for model 8 (i.e. 30-degree column).

The 3D potterbot SLX-2 (Scara) robot can be fitted with a variety of nozzle sizes ranging from 1mm to 25mm.

The study models were printed using the 3.5mm diameter nozzle. The nozzle size is an important consideration before producing G-code (see figure 4) as various object designs are contingent on factors such as overall dimensions, level of detail required and angle of slope. Waste material is another consideration and clay loads can be loaded appropriate for the object size. The maximum build envelope height for XLS-2 Scara robot is 1828mm diameter and 1143mm Z height. It can be customized to print 2743mm diameter and 2590mm Z height.

Table 2. Selected causes of failure modes.

Models size/Scale	Failure
Appearance Designed Model 4	The start point of the extruder is hard to predict. The first layer printed outside the area of the intended base board. (see Fig.7 (1))
All 9 models	The size of the model is limited by extruder printing information such as the Nozzle Diameter in fig.5 and G-code in fig.6 for 30-degree column.
Squares, Rectangles and Arches	Due to the pressure in the extruder, the machinery cannot stop printing the clay resulting in wasted materials. (see Fig.7 (2) & (3)).
Appearance Designed Model 2 (100%)	The Shape structure changed as the size and scale of the models was modified. Same design, original size (left) collapsed, but the half size (right) printed successfully (see Fig.7 (5) & (6)).
Column models	The shape of the design is limited as the clay is soft and cannot stand by itself (see Fig.7 (9)).
All 9 models	The surface finish can be affected by the air bubbles, material may have flaws (see Fig.7 (11)).
All 9 models	Shrinkage and cracking occurred damaging the model. (see Fig.7 (12)).
Priming edge and the first layer of all models.	The start layers do not work well. The first layer is compressed, possibly caused by the height of the nozzle or the uneven moisture level of the board. The board is not flat due to the difference in water absorption (see Fig.7 (7)).
Square, Rectangle and Arches.	Due to mechanical errors the machine stopped working for three times during printing of simple shape models (Square, Rectangle and Arches).

Figure 7 shows all relevant images of the failure models. In order to observe the effect of slope in failures of the 3D printed models, the angle of the surface was changed from 0-degree to 60 and 80-degree for M8 and M9 respectively.

In the column-slope model (M6), the top section has

a collapse trend from 80% to 120%. The middle section of the sample with the scaled model of 120% (i.e. 20% larger sized printed) collapsed and cracked.

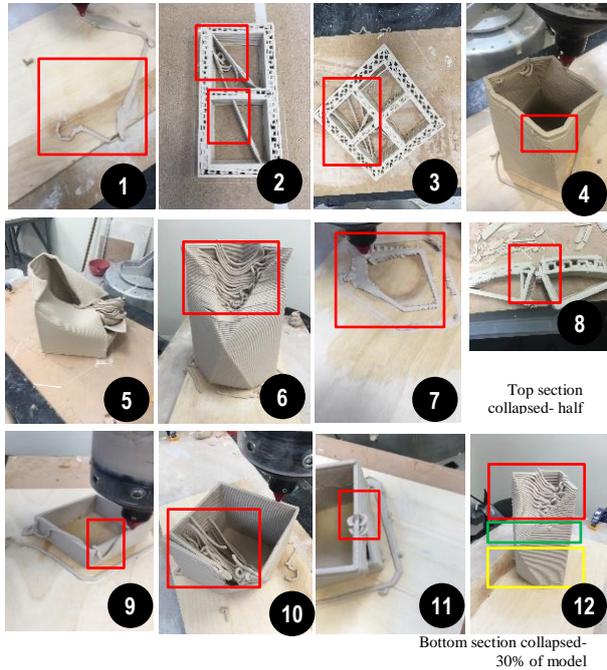


Figure 7. Selected 3D printed of failed models.

Table 3. The frequency of the issues during the 3DP process for 56 models.

The Issues during the 3D printing process	Frequency
Small Air bubbles.	44
Large Air bubbles and flaws (Fig.7 (11)).	41
One edge is wider, and the opposite is thinner due to one board moisture inconsistency (Fig.7 (7)).	8
The structure of rectangles and squares changed after scaling 130% of original size. (Rectangles and squares, Fig 7 (2)).	6
The top section collapsed for Column (M1) and Column Slope (M3) (see Fig.7 (6)).	6
Preparation time is much longer due machinery faults, generally issues getting the nozzles ready.	5
Total completion time is longer as G-code created for motion programming of machinery is inefficient.	4
The bottom section bent, and the clay path distorted for Column (M1) (see Fig.7(12)).	4
The paths distorted on top section for Column (M1) and Column Slope (M3) (see Fig.7(6)).	4
The model begins to collapse as the nozzle deposits clay a little further outside its intended path for Column (M3) (Fig.7 (4)).	3
The paths do not form a circle only a line for Column (M1) (see Fig.7(6)).	3
The center parts started printing for Column Radian (M2) (see Fig.7 (10)).	3

The machinery hardware stops working for a while	3
The path in the center at this layer cut off during the printing process for Column (M1) (see Fig.7 (6)).	2
The top paths distortion is more severe than before for Column (M1) (see Fig.7(12)).	2

The diameter of the cylinder is proposed as 10cm in models; however, the diameter in the 3D printed model with 0-degree is 96mm. Observation shows that the collapse starts at a layer with 20-degree slope in the cylinder (M8). Because the 60-degree cylinder shape is more like a triangle, which is the most robust shape in construction, the base diameter is smaller than the 45-degree cylinder and the same with the 20-degree cylinder's base diameter.

Table 4. Shrinkage Table after 7 days for 14 models in different slope.

Models code	Average shrinkage in each side
Cylinder 0 slope	2.56%
Cylinder 10 degree	3.16%
Cylinder 20 degree	6.39%
Cylinder 30 degree	5.10%
Cylinder 45 degree	9.70%
Cylinder 60 degree	12.51%
Column 0 degree	3.50%
Column 10 degree	4.35%
Column 20 degree	4.11%
Column 30 degree	2.96%
Column 45 degree	3.26%
Column 60 degree	2.68%
Column 70 degree	3.18%
Column 80 degree	5.56%

Note: Base on the laboratory personnel experience, the normal shrinkage rate should around 10%.

## 4 Results

Table 4 shows the descriptive analysis of the models. It shows that the mean time per layer for the models varies from 0.27 to 2.85 minutes.

An analysis of variance (ANOVA) test was employed to examine whether the differences of means are significant or not. Figure 5 shows the means for each model.

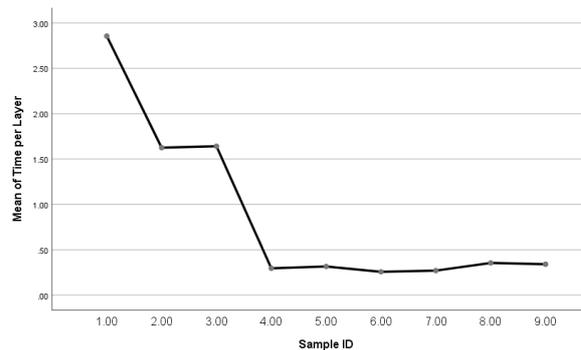


Figure 5. Mean for time per layer for all eight models.

The analysis shows that there was a statistically significant difference between models 1, 2 and 3 with all other models (e.g. from 1 to 8) except 2 and 3 as determined by one-way ANOVA ( $F(8,47) = 20.782$ ,  $p = 0.000$ ). The Tukey post hoc test was applied and showed that the time per layer to complete the first model was statistically significantly higher than all other models ( $2.85 \pm 0.91$  min,  $p < 0.003$ ). The time was second highest for model 2 ( $1.63 \pm 0.66$  min,  $p < 0.019$ ), and model 3 ( $1.64 \pm 0.59$  min,  $p < 0.04$ ). There was no statistically significant difference between model samples of the model 2 and 3 ( $p = 1.000$ ). There was no statistically significant difference between all models 4, 5, 4, 7, 8 and 9 with each other ( $p = 1.000$ ).

Table 5. Descriptive analysis for time per layer.

M	N	Mean	Std. Deviation	95% Confidence Interval		Minimum	Maximum
				Lower	Upper		
1	12	2.86	0.91	2.28	3.43	1.61	4.27
2	12	1.63	0.67	1.20	2.05	0.66	2.63
3	6	1.64	0.59	1.02	2.26	0.91	2.58
4	3	0.30	0.04	0.20	0.39	0.26	0.34
5	3	0.32	0.05	0.20	0.43	0.27	0.36
6	3	0.26	0.04	0.15	0.36	0.22	0.30
7	3	0.27	0.05	0.15	0.39	0.22	0.32
8	6	0.35	0.04	0.31	0.40	0.30	0.42
9	8	0.34	0.02	0.33	0.36	0.32	0.36
T	56	1.28	1.14	0.98	1.59	0.22	4.27

Note to table: M refers to model, N refers to the number of layers per model, Mean refers to the time spent for each layer, T refers to Total.

## 5 Discussion

3D printing has been used in manufacturing for many years, but whilst its adoption into the construction industry has been slow, it is currently a growing area of development for building construction. Previous studies have generally investigated potential materials and their

properties for 3D printing as well as adapting or designing 3d printing technologies for effective delivery on construction sites. However, investigations into combining complex geometries and construction by 3D printing have received less attention.

The potential advantages of 3D printing in construction are significant. They include not only not only increased efficiencies pertaining to financial and environmental resources but, also, the capacity for mass customization of designs to meet aesthetic, functional and structural purposes. Previous studies and realized 3D printed houses have shown the potential for minimization of construction waste from precise material deposition and eliminating the need for of formwork. Previous studies have also shown the potential for increased safety on construction sites. However, many factors need to be addressed before 3D printing can be fully utilized for complex shapes in construction. They include further research into material properties to a attain structurally stable material, not just for longevity but crucially, during printing. Challenges for 3D printing include material setting time, stability during printing, deformation, shrinkage and bonding between layers. Material behaviours require further investigation under a range of conditions to achieve a robust material that can take structural load during and after printing.[4].

This study examined the capability of 3D printing for producing complex geometries. Key factors such as shrinkage, time per layer or speed and material wastage were examined in the laboratory. We faced several challenges during the production of different models. The limitation during the laboratory experimentation was the lack of control of the machine by the user. These types of factors are very important on a real construction sites, when a worker needs to change specific dimensions, angles or position of the nozzle. To address this issue, we would recommend human-printing collaboration strategy, which helps human and 3D printers to work side by side to complete the construction of the item or structure.

Construction sites are not predictable and rarely flat and even surfaces or environments and so many adjustments are required to address issues such as slope of site, humidity and environmental factors like wind.

This study will be replicated with a variety of materials and model designs not with the intention of creating the ideal environment for 3D printing but by addressing the issues in their application on real construction sites.

Model designs can play an important role in creating feasible structural shapes to understand and predict how material properties change with curvature and slope of surfaces. However, other factors should be further investigated such as the volume of waste materials, total cost including the operation cost, optimization of nozzle path, and material properties such as brittleness of clay

and concrete. Another issue is increasing the level of automation of the entire process from design to construction.

In line with some of previous findings in different contexts [5,4,6,7], several limitations of the 3D printer were observed in our experiments. The PotterBot XLS-2 Scara was not able to generate digital data in terms of motion speed, volume of clay used and total length or volume of the printed layers. The process of 3D printing, from digital modelling in CAD programs to converting to machine instruction G-code in a CAM program, and operation of hardware requires vastly different skill-sets and knowledge than is common in current construction practices. CAD modelling software packages, with the exception of relatively costly Rhinoceros 3D Modelling package with plug-in RhinoCam, CAD platforms cannot directly communicate with 3D printers and intermediary Computer Aided Modelling (CAM) programs are required to convert vector based data to G-code to communicate with the machine, meaning that currently available software packages do not allow automation or real-time response between digital modelling and 3D printing. However, many advantages were also observed. 3D printing provides the possibility for continuous construction, not limited to working hours or visibility during sunlight with minimal supervision. Another further positive observation was the low level of noise produced during the 3D printing process which was negligible compared to that of construction sites. As predicted in numerous previous studies, the perceived and assessed safety level of using the PotterBot was of much lower risk level than for other common construction methods and has the potential to reduce injuries and fatalities in the construction industry.

## 6 Conclusions

This study aimed to examine the capability of 3D printing to produce complicated geometric and volumetric designs. Eight models were designed and 56 models were created in the laboratory by a 3D printer called PotterBot XLS-2 Scara robot. The entire production process was carefully observed and several factors including material setting time, stability during printing, possible unsupported material overhang, deformation, shrinkage and bonding between layers. for all 56 models were recorded. The results show that the first three models are significantly different than the last four models. In addition, the studies show that the waste material and motion path can be challenging for models with complicated designs. The key contribution of the paper is to compare several complicated models to measure how curvature and unique models can affect potential construction practices for creating complex curves and forms on construction sites without the need

for formwork or reinforcements.

As discussed, future studies will continue to focus on adapting 3D printing processes, currently suitable for controlled lab environments, to real construction sites with a focus on automating and simplifying the process to enable the adoption of 3D printing into house construction.

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