Chapter

# Computational Workflow for Three-Dimension Printing in Construction: Digital Tools and Methodological Limitations

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## Abstract

Three-dimensional printing in construction (3DPiC) is known as a trending technology in the construction industry. While scholars and practitioners seek to learn more about the applications of 3DPiC, there are no efficient workflows and open data sets available for further investigations. This paper intends to present the data produced in a laboratory for creating new models. The paper first presents the experimentation data collected from 60 models, and selected thermal digital images can be used for further sustainability analysis. The recorded data includes the time of crafting each layer of the model, the total time of creating a model and thermal measures. Based on the 60 experimentations and an intensive literature review, the paper presents a proposed computational workflow, including the use of Revit, Dynamo, Fusion 360, Navisworks and a selected 3D printer, which can be utilised for further data collection and analysis in the field. This model will assist in automating the cost estimation as an upgrade for 3DPiC. This paper is helpful for scholars and practitioners since it shows how laboratory data can be helpful for construction operation design.

**Keywords:** 3D printer (3DP), 3DP in construction (3DPiC), digital model, computational workflow, clay, material, building information modelling (BIM), Revit, dynamo, fusion 360, Navisworks, quantity surveying, leanness, waste

## 1. Introduction

3D printing (3DP), namely additive manufacture, was introduced many years ago. The use of 3DP applications has risen recently in various disciplines [1–4], but still is very low in the construction industry due to many challenges and limitations. Furet et al. [5] state that the application of digital technologies including building information modelling [6, 7], virtual reality [8], laser scanner and lidar ([9–11], Sepasgozar et al., [12–16]) is increasing in construction [17, 18]. Then, Furet et al. [5] suggest that the next step will be the implementation of 'three-dimensional printing in construction' (3DPiC) on a wide scale.

The utilisation of 3DPiC can be highly beneficial to the construction industry in several ways, including the possibility of topologic optimisation offering customised forms fit purpose, the possibility of complex geometric parts, thermal optimisation and 'leanness' such as reduction of labour and material wastes [5]. However, the process of technology implementation in construction is challenging and needs to be investigated by conducting many empirical experiments [19]. The process of technology adoption is generally complicated and can be affected by many factors, including usefulness, ease of use, vendors support and organisation policy and the users' current infrastructures [15, 18, 20–22]. This paper aims to explore the challenges of 3DPiC by creating several laboratory models. Niemeläa et al. [23] present the result of some of the created models to show how curvature and unique designs may affect the construction operation process where complex curves and forms should be created on sites without using formworks or other traditional tools. This paper also intends to present a proposed workflow for computing the cost of the model in real time. This will be further examined in future investigations.

**Figure 1** shows different digital tools, operation methods and materials of 3DPiC. There are six different operation methods, for instance, D-shape and contour crafting (CC) and concrete printing. D-shape was developed by Enrico in 2007 [24], and materials used by this technology are sand, salt and an inorganic binding agent [1]. The CC was introduced by Khoshnevis in 1998 [25] and uses a computer-controlled robot or crane to work efficiently with a short setting time and optimised hydraulic ratio [1]. Concrete printing is a useful method for concrete mortar [1]. This paper adopts the CC method to produce small-sized models in laboratory. This paper presents the research method flowchart, recorded observations during the experimentation process and the proposed computational workflow for future evaluations.

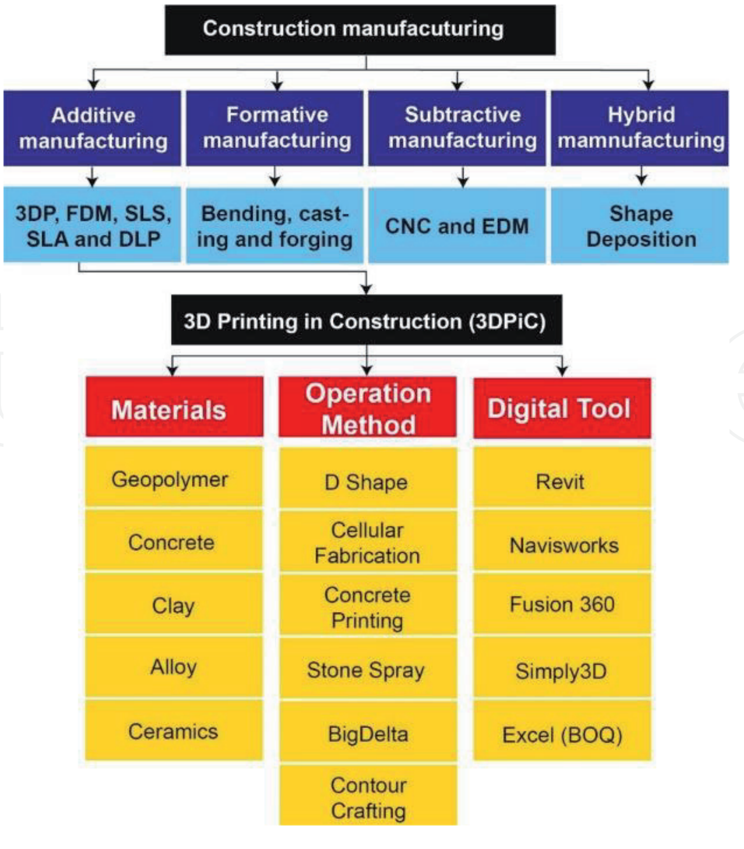


**Figure 1.**
*Digital tools, operation methods and materials for 'three-dimensional printing in construction' (3DPiC). Note: FDM: Fused deposition modelling; SLS: Selective laser sintering; SLA: Stereolithography; DLP: Digital light processing; CNC: Computerised numerical control; EDM: Electrical discharge machining; BOQ: Bill of quantities.*

This chapter aims to present a workflow that is developed based on the investigators' experimentations with the support of a wide range of data and records, including 60 laboratory-scale models. These models are structural elements and architecture models in different sizes by using different clay materials. The proposed computational workflow considers Revit, Navisworks and Fusion 360 for estimating the differences between the virtual and physical models and can be useful for estimating the cost of the 3DP models.

## 2. Research method and data collection

In order to explore the challenges of creating complex geometrical forms and digital tool functions, a series of experiments are conducted. The Mix method, which focused on both qualitative data and quantitative data, was adopted for this research [26, 27]. This paper adopted the quantitative research method as the aim of the laboratory experience is to turn the laboratory observations into statistical analysis. Qualitative methods were chosen due to scarce research studies in this area, and it is essential to introduce a new set of data of the 3DPiC [26, 27]. In order to record the observations, two pieces of equipment and three software programs were used and will be briefly presented in the following section. The data description and analysis are presented in the following subsections.

### 2.1 Tools and equipment

A 3D printer, namely Potterbot SLX-2 (Scara) printer (see **Figure 2 (a)**), was used to create 60 models, and a thermal scanner 875-2i (see **Figure 2 (b)**) was used to measure thermal factors such as temperature and carbon.

### 2.2 Data description

The data is collected through printing 60 laboratory-scale models, comprising 56 models created by clay and four created by 'paper clay'. There are 32 of them that are structural elements such as arches, rectangles and squares in different scales.

(a) (b)

**Figure 2.**
*Tools used in this research: (a) Potterbot SLX-2 (Scara) printer; and (b) thermal imaging scanner 875-2i.*

The four paper clay models are the architecture models. Moreover, 14 models of them are the columns in different twisting degree and the cylinder in different slope degree.

Two models were printed twice due to the 3D printer running out of clay during the printing process. The models could not be continuously printed after refilling the extruder with clay because the previous layers of the model had hardened quickly. The thermal digital images were collected five days after producing each model by Testo 875-2i for the thermal and humidity analysis also can be used for further sustainability analysis. These images can be used for further analysis, such as building material analysis, human comfort analysis, insulation issues, connection issues between the layers, the energy embodied and radiation, design optimisation analysis, scheduling progress management of printing and post-maintenance.

### 2.3 Data collection

**Figure 3** shows the selected images of nine different models created in the laboratory. There were waste materials produced during the experimentations due to the nozzle travelling path, for example, **Figure 3 (c–h)**. This shows that the optimisation of the path and experimentations on smaller scales are required before the full-sized practice for each written coding to ensure the arm and nozzle path will be desirable with less waste materials.

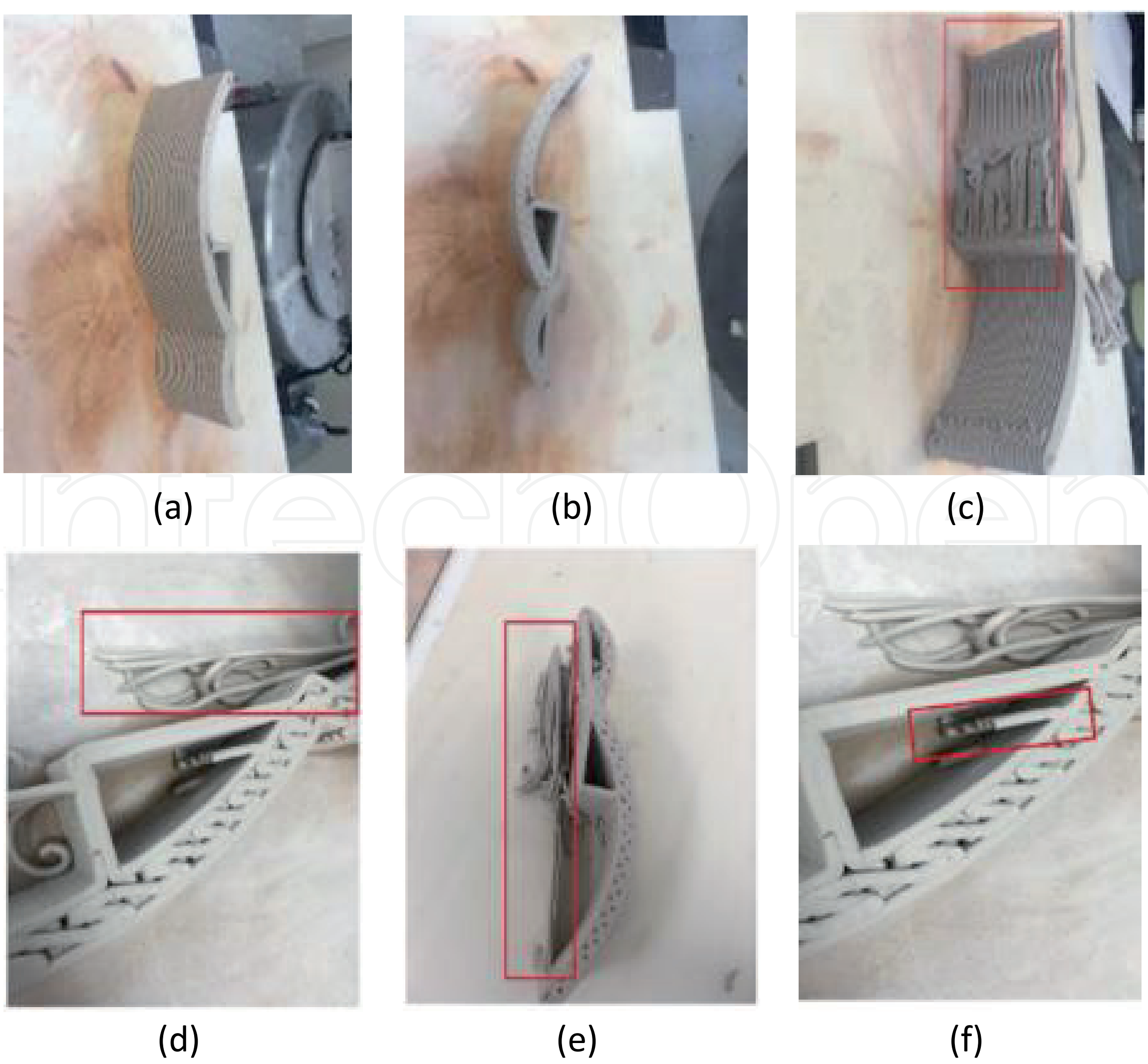


**Figure 3.**
*Arches models at different scales. (a–c) Arch 50% of original size; (d–f) arch 80% of original size.*

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The flaws in the models are caused by bubbles errors. There were some air bubbles in the 3D printer extruder, and when the materials that involve the air bubbles had been push out, the small flaws and sound were produced. In addition, producing complicated forms was also challenging, and the designed shapes were not produced, as shown in **Figure 4 (a–b, d–g, i** and **k–l)**. The red rectangles shown in the photos refer to waste materials produced during the casting process. The observations show that information flow and controlling the machine to produce desirable forms require a more efficient workflow to save the materials and also for cost estimation.

There are thermal digital images of one of the paper clay architecture models (see **Figure 5**), and different colours show different temperature ranges. The humidity digital images are attached in the appendix.

**Table 1** shows the recorded time per layer for 14 models, with columns in different twisting degrees and the cylinder in different slope degrees, and it does not


**Figure 4.**
*Rectangle-shaped models at different scales. (a) Rectangle 100% of the original size; (b) rectangle 110%; (c) rectangle 120%; (d-e) rectangle 130%; (f) rectangle 140%; (g) rectangle 170%; (h) rectangle 180%; (i–l) square 100% of the original size.*

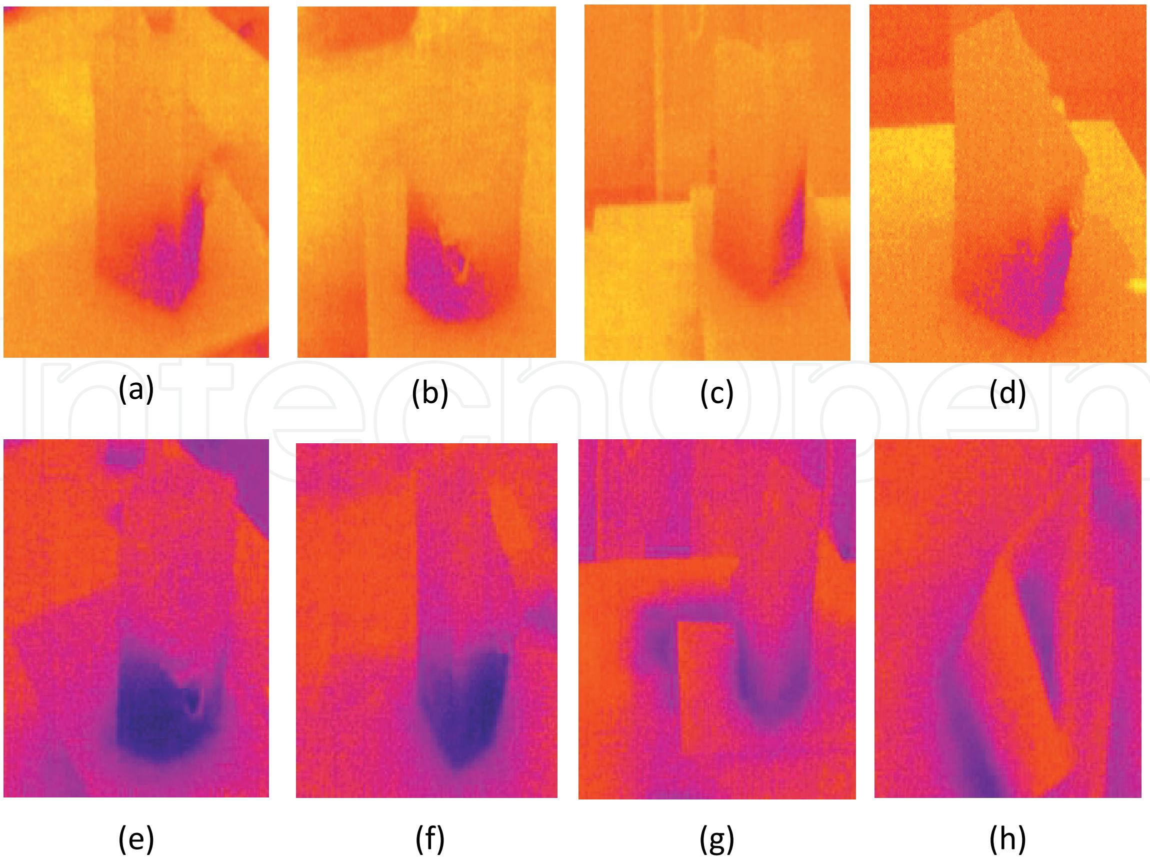


**Figure 5.**
*Thermal digital images of one of the architecture models. (a–d) Thermal image 24–28 degree; (e–h) thermal image 25–29 degree.*

| Shape | Shape ID | Sample | Scale% | Slope (degree) | Layers | Total Time | Time/Layer |
|---|---|---|---|---|---|---|---|
| Cylinder | 1 | 1 | 100 | 0 | 25 | 0:10:29.430 | 0:00:12.736 |
| Cylinder | 1 | 2 | 100 | 10 | 25 | 0:08:46.310 | 0:00:12.110 |
| Cylinder | 1 | 3 | 100 | 20 | 25 | 0:08:46.650 | 0:00:11.400 |
| Cylinder | 1 | 4 | 100 | 30 | 22 | 0:08:31.870 | 0:00:10.452 |
| Cylinder | 1 | 5 | 100 | 45 | 22 | 0:07:04.340 | 0:00:09.155 |
| Cylinder | 1 | 6 | 100 | 60 | 21 | 0:06:13.560 | 0:00:06.847 |
| Column | 2 | 1 | 100 | 0 | 60 | 0:19:12.200 | 0:00:15.735 |
| Column | 2 | 2 | 100 | 10 | 60 | 0:18:57.510 | 0:00:15.752 |
| Column | 2 | 3 | 100 | 20 | 60 | 0:21:25.450 | 0:00:15.855 |
| Column | 2 | 4 | 100 | 30 | 56 | 0:17:58.850 | 0:00:15.702 |
| Column | 2 | 5 | 100 | 45 | 54 | 0:19:18.860 | 0:00:16.000 |
| Column | 2 | 6 | 100 | 60/30 | 60 | 0:21:10.760 | 0:00:15.859 |
| Column | 2 | 7 | 100 | 70/20 | 60 | 0:20:50.800 | 0:00:15.770 |
| Column | 2 | 8 | 100 | 80/10 | 60 | 0:21:06.390 | 0:00:15.720 |

**Table 1.**
*Characteristics of two models with different slope degrees (14 models).*

include the start, priming edge and finish time. The priming edge is used to make the extruder ready for printing, and the finish time is the end running process for the extruder. The design diameter of the cylinder is 10 cm; however, the diameter

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| Shape | Shape ID | Sample | Scale% | Slope | Layers | Total Time | Time/Layer |
|---|---|---|---|---|---|---|---|
| Column | 1 | 1 | 100% | 0 | 100 | 0:29:14.010 | 0:00:14.883 |
| Column radian | 2 | 2 | 100% | 0 | 100 | 0:30:49.180 | 0:00:15.874 |
| Column slope | 3 | 3 | 100% | 0 | 123 | 0:30:41.840 | 0:00:12.481 |
| Column dome | 4 | 4 | 100% | 0 | 97 | 0:24:35.840 | 0:00:13.307 |

**Table 2.**
*Architecture models (recorded time).*

| Shape | Temperature (degree) | Humidity (rh) | Co2 (ppm) |
|---|---|---|---|
| Column | 27,1 | 75,1% | 481 |
| Column radian | 27,0 | 76,1% | 456 |
| Column slope | 27,0 | 76,8% | 469 |
| Column dome | 27,1 | 76,9% | 442 |
| Room temperature | 27,1 | 76,1% | 476 |

**Table 3.**
*The detailed information for the architecture model in **Table 2.***

of the actual printed model with a 0-degree wall slope is 9.6 cm. The model with a 20-degree slope had a collapse trend. The most serious deformations occurred at the 30-degree and 45-degree columns.

**Tables 2** and **3** show the detail recorded time and the temperature and humidity information for architecture models, respectively. Also, recorded time does not include the start, priming edge and finish time.

## 3. Proposed computational workflow and future directions

Our experimentations show that controlling the 3DP during construction is challenging and may affect quality due to the unexpected flows and wastage. According to the laboratory observation, most of the 3DP models presented in this chapter have the waste part. Thus, it is necessary to develop efficient workflows to ensure the 3DP process is efficient and easy to estimate the exact volume materials used for 3DP models and further manage the costs. While different algorithms are presented in the literature, including the travel salesman problem algorithm (TSP) used to select the shortest path [28], there are not enough workflows offering an efficient method for controlling and operating the system for construction purposes, especially for materials estimation and costs management. There is an urgent need to develop new workflows that are interoperable with new hardware and software programs. This may increase the operational control of casting processes, the quality of the produced models and calculate the wasted materials. **Figure 6** shows a proposed workflow for the integration of additive manufacture with 5D BIM to compare the cost difference between digital measurement and real-time production. This workflow intends to generate the cost of the produced work with real-time measurement of produced layers and then compares with costs generated based on the measurement from digital software.

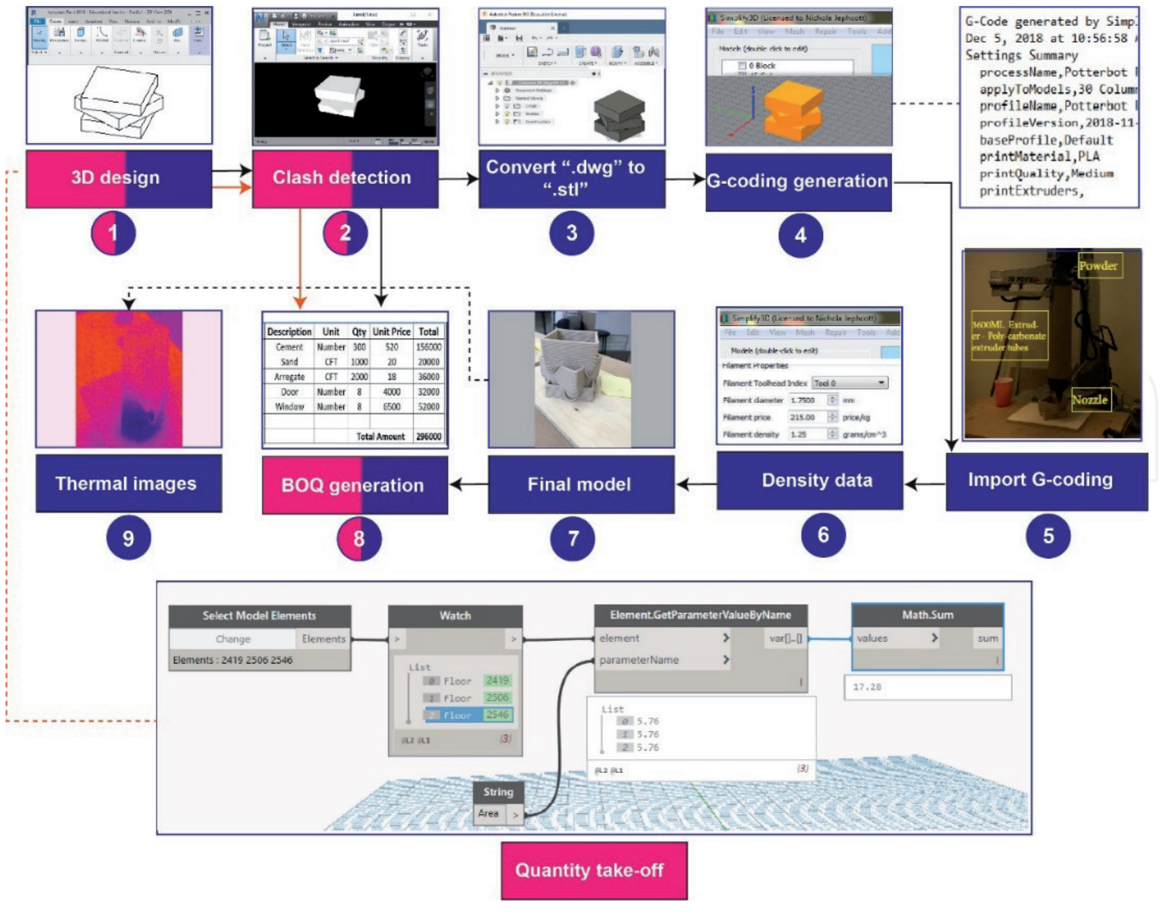


**Figure 6.**
*The proposed workflow for real-time and design digital cost estimation of contour craft objects.*

The real-time measurement consists of nine stages:

Stage 1: the 3D model will be created in the Revit; it can be imported into Navisworks by.*rvt* or.*rfa* extension.
Stage 2: clash detection can be done through Navisworks; the schedule and other cost information are collected and imported into the Bill of Quantity (BOQ) [29]. The 3D model is saved as a.*dwg* format because it can be used in Fusion 360. In addition, the design quantity information can be extracted from Revit with Dynamo Extension [30] and then can be imported into BOQ.
Stage 3: import the 3D model into Fusion 360, and convert the model field into.*stl* extension. Then, the CAD model can be used in the slicer software 'Simplify 3D' to generate the G-coding. This is required because the.*dwg* format cannot be used directly for generating G.
Stage 4: Simply3D is used to slice the 3D models into the printable layer; the G-coding automatically generates the required coding.
Stage 5: USB with G-coding into the drive board of a 3D printer.
Stage 6: density (p) is computed by Simply3D, and by measuring mass (m) of the real physical model to estimate the volume (v) in each layer.
Stage 7: final physical model in the desired scale is created.
Stage 8: import the real physical volumetric data to the BOQ, and estimate the actual cost.

A sensor or a material flowmeter can be used during the printing process. There are several different sensors available in practice, such as the concrete flowmeter offered by 'Jiangsu Sipai Instrument Co.' in 2014. The detection range of SP-LDE concrete flowmeter is from 0.0636 to 4521.6 m3/h [31]. During casting, the volumes of casted parts will be measured by the installed sensor, and the data can be compared with the estimation given by Revit.

Stage 9: the thermal images are generated using a thermal scanner. The thermal images used in this paper are recorded five days after the casting process of each model.

Some of the stages can be merged or changed if other hardware or software programs are used. For example, if Dynamo is used, the design quantity information would not be required to extract from Revit. Future studies should focus on examining the proposed workflow and providing more details of each stage. Other new technologies also should be investigated to reveal what type of software or hardware technologies are interoperable and can be used efficiently for 3DPiC.

## 4. Conclusions

This paper aimed to present a series of data collected during the process of designing and creating 3DP models in different sizes by using different clay materials. In addition, the paper proposed a workflow for collecting required digital data for estimating the physical progress of casting the model, volumes and associated costs.

This is a step forward to fill the gaps in knowledge to control 3D printing in an efficient way, acquire digital data for cost measurements in real time. The workflow can be examined as future studies and also can be revised by combining the proposed software programs with other new technologies to produce more information for progress monitoring and estimating. While the major limitation is that some of the full-size practices cannot be experienced, the flow of digital information can be tested in the laboratory. In addition, the observations and the data presented in this paper recommend that construction practitioners should test the programming codes, and the parametric design at the laboratory scale before the full-scale practice for optimising the movements of the 3D printer arm, quality and waste controls is undertaken.



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**Dataset:** https://doi.org/10.6084/m9.figshare.8427023.v1
**Dataset license: CC BY 4.0**

## Appendix

See **Figure** 7.

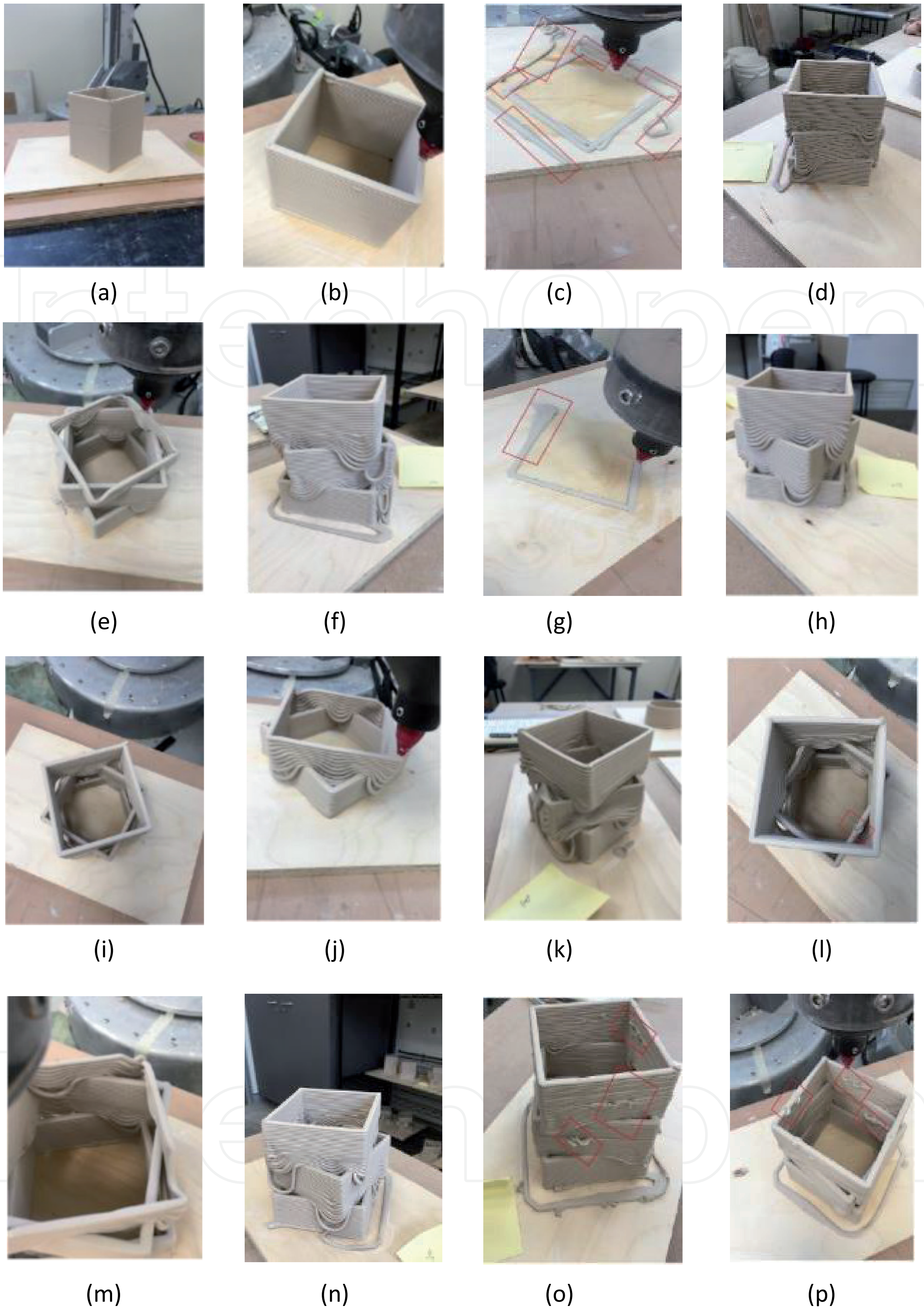


**Figure 7.**
*Column models at different twist degrees. (a-b) Column 0 twist degree of original design; (c-d) column 10 twist degree of original design; (e-f) column 20 twist degree of original design; (g-h) column 30 twist degree of original design; (i-j) column 45 twist degree of original design; (k-l) column 60 (-30) twist degree of original design; (m-n) column 70 (-20) twist degree of original design; (o-p) column 80 (-10) twist degree of original design.*

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