Novak, J. and O'Neill, J. (2019), "A design for additive manufacturing case study: fingerprint stool on a BigRep ONE", *Rapid Prototyping Journal*, Vol. 25 No. 6, pp. 1069-1079.
https://doi.org/10.1108/RPJ-10-2018-0278

Introduction

Extrusion-based Additive Manufacturing (AM, also called 3D printing) is the most ubiquitous form of AM technology; hardware costs have rapidly declined over recent years, particularly as key patents have expired (Gibson et al., 2015, Quinlan et al., 2017), resulting in an abundance of affordable and versatile machines (Campbell et al., 2012, Gao et al., 2015). Known as Fused Filament Fabrication (FFF), or Fused Deposition Modeling (FDM), extrusion-based AM technology pushes a polymer filament through a print head, where it is heated to a semi-viscous state, and extruded out of a nozzle. The molten polymer is laid down as a single horizontal cross-section of the part being printed, before the next layer is printed on top in a repeating layer-by-layer process until the final object has been produced.

Alongside the improving performance and reducing price of desktop FFF machines (Benson et al., 2018, Greenfield, 2017, Krassenstein, 2014), the technology has also recently begun to expand significantly beyond the desktop scale. There are several ways this is being achieved, including the scaling up of classical desktop 3D printing machines, which is the focus of this study, as well as novel modifications to robot arms that allow the deposition of material outside the bounds of a formally constrained build volume (Keating and Oxman, 2013), or the development of cable-suspended robots within a room (Barnett and Gosselin, 2015). A notable development demonstrating the ability to scale up a more traditional Cartesian 3D printing method is Big Area Additive Manufacturing (BAAM), developed at Oak Ridge National Laboratory (ORNL, United States of America) and featuring a build envelope of up to 6 × 2.5 × 1.8m (Kishore et al., 2017). The printer features a Cartesian gantry system conceptually similar to many desktop 3D printers, however, rather than using spools of polymer filament to feed the extruder mechanism, polymer pellets are fed through a screw system similar to that used in injection molding, allowing higher throughput and the use of a cheaper material source for such large objects (MacDonald et al., 2017). Numerous studies have examined the qualities of 3D printing at such scale, for example the structural and mechanical properties of parts (Duty et al., 2017), the thermal properties of 3D printing composites (Compton et al., 2017), and the novel applications of computer vision (MacDonald et al., 2017) and infra red pre-heating systems (Kishore et al., 2017) to improve the performance of resultant parts. At such scale this technology requires significant space and capital (hundreds of thousands to millions of dollars), being suitable for large-scale industries like automotive and aircraft manufacturing.

Between both the desktop and BAAM scales are an emerging class of large area AM machines utilizing FFF extrusion methods, typically with print dimensions starting at one meter for all axes. Commercially available examples include the 'BigRep ONE' (BigRep, Berlin, Germany) with a print volume of 1.005 × 1.005 × 1.005m (Cartesian style printer), the 'Delta WASP 3MT' (Wasp, Massa Lombarda, Italy) with a print volume of Ø1 × 1.2m (delta style printer), and the 'Tractus3D T3500' (Tractus3D, Ammerzoden, The Netherlands) with a print volume of Ø1 × 2m (delta style printer). Such machines cost in the tens of thousands of dollars, making them suitable for smaller manufacturing facilities, design and engineering firms, and universities. Due to the emergent quality of such machines, little peer reviewed literature exists and designers and engineers must enter into experimental testing in order to evaluate the opportunities and limitations of each new machine outside the manufacturer claims and specifications. Published research typically focuses on standardized test pieces such as those described by ISO 572-2:2012 for tensile testing of plastics (Ahn et al., 2002, Zelený et al., 2014), or simple geometries like cylinders (Vasilescu, 2017) and blocks (Armillotta et al., 2018) to provide a quantitative understanding of material and print properties of a specific AM process.

However, there are limitations to such an approach, with the data not providing design engineers and technicians with an understanding of the limitations and challenges of producing more complex geometries, such as those that are not possible with traditional manufacturing. Therefore, this experimental study is led through design and production of a novel piece of furniture specifically designed for additive manufacture on a BigRep ONE machine. The core criteria considered by the designer were:

1. A budget of $1500AUD for filament, limiting the amount of material used (costs in ProtoSpace for researchers are calculated on material use only).
2. A print time <5 days so the printer would not be unavailable for other projects for more than one working week.
3. A one-off design specifically created for additive manufacture on a BigRep ONE.
4. A complex form that could not be manufactured using traditional technologies.
5. A functional requirement to allow adults to sit on the design.
6. Use no support material.

In order to fulfill these criteria, the design process iteratively shifted from design to simulation and process control in a cyclical process, resulting in a functional stool that physically embodies the capabilities and limitations of the BigRep ONE. Settings related to material cost, print time, nozzle diameter, layer height and perimeter walls were documented, analyzed and modified~~,~~. Additional data was collected about the overall dimensional accuracy and surface roughness properties of the printed result. ~~providing~~This provides new knowledge for designers, researchers and industry professionals about this relatively new 3D printer, and shows the opportunities and limitations to using a design-led approach for learning machine capabilities.

Method

This study aligns with an increasing body of literature describing a Design for Additive Manufacturing (DfAM) process, most recently being defined as “aiming to take advantage of the unique capabilities of AM to (i) design and optimize components according to the functions of the product/component and the requirements of the selected AM process for production; and (ii) rethink, redesign and refine an existing product/component, utilizing the characteristics of AM to improve the functionality” (Pradel et al., 2018). While numerous researchers suggest there is a lack of consensus defining a DfAM workflow (Boyard et al., 2013, Pradel et al., 2018, Thompson et al., 2016), a framework proposed by Kumke et al. (2016) provides tangible guidelines that can be adopted by design engineers from the initial stages of a project through to final manufacture. A fundamental feature of Kumke et al.’s (2016) framework is the classification of a DfAM process into three distinct phases: planning and clarifying the task; conceptual design; embodiment design and detail design. The first planning phase has been introduced in the earlier section of this paper, with six core criteria driving the study. However, unlike Kumke et al.’s (2016) framework, where the selection of an appropriate AM technology occurs after phase 2, this study deviates from the framework through the selection of a specific 3D printer from the outset. Therefore, the qualities of this printer will be defined through the following sections, informing phase two (conceptual design) of the project to follow.

BigRep ONE Specifications

This study utilizes a BigRep ONE 3D printer located within the ProtoSpace, a new additive manufacturing research space at the University of Technology Sydney (UTS), Australia. Figure 1 shows the printer used for this study within the ProtoSpace, which was installed in 2018. Manufactured by the German company BigRep, the first public release of the BigRep ONE printer was in 2014 (Koslow, 2017), and the latest version 3 of the printer features the specifications listed in Table 1. More specific details related to the settings used for printing this project will be described in the results section of this paper.

Figure 1. BigRep ONE 3D printer in the University of Technology Sydney ProtoSpace

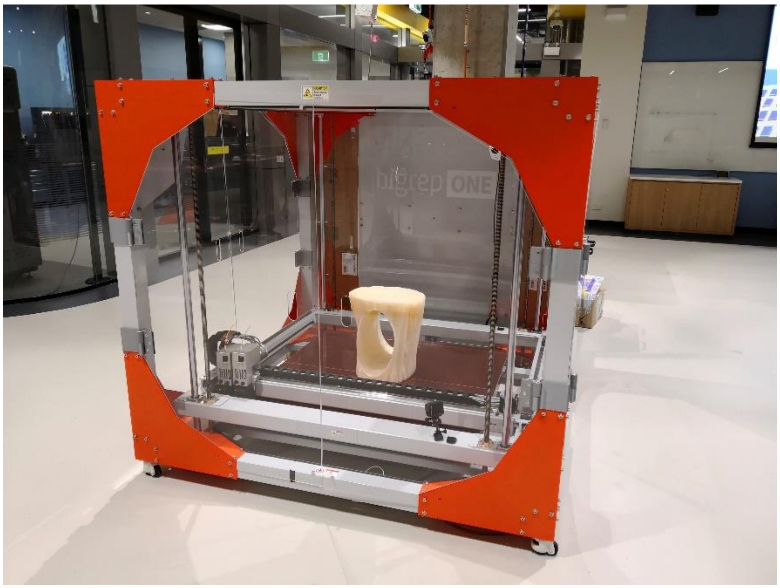


Table 1. BigRep ONE v3 specifications

Machine Type	Cartesian, FFF material extrusion
Build Volume	**x** 1005 **y** 1005 **z** 1005 (mm)
Machine Size	**x** 1850 **y** 2250 **z** 1725 (mm)
Machine Weight	Approx. 460kg
Nozzle Diameter	Power extruder = 0.6, 1.0, 2.0mm
Layer Height	0.4 - 0.8mm (standard extruder) 0.15 - 1.4mm (power extruder)
Extruder	2 x modular extrusion heads
Power	208V-240V, 16A, 50/60Hz
Filament Size	2.85mm filament
Material Type (for this study)	Polylactic Acid (PLA)
Bed	Heated
Interaction	On-board touch screen with GUI

Unlike some large 3D printers such as BAAM or the Delta WASP 3MT, the BigRep ONE is limited to spools of 2.85mm filament rather than offering a pellet mechanism for extrusion. As a result, the printer is very similar to common desktop machines with scale the most notable difference. At the time of writing, certified filaments supplied by BigRep specifically for the printer include Polylactic Acid (PLA), Polyethylene Terepthalate Glycol (PETG), Polyvinyl Alcohol (PVA, for support material), and two special Biopolymers for high temperature resistance (PRO HT) and high speed (PRO HS), although other brands and types of filament that suit the machine specifications can also be used. Due to the large print volume, large spools up to 8kg can be loaded onto the printer, and several spools can be held at a time, although only two can be feeding into the two direct drive extruder heads at any time.

As shown in Figure 1 the BigRep ONE is enclosed on its four sides, with clear plastic doors mounted to hinges on three of the sides allowing the operator to access the print plate and mechanisms. The top of the printer is not enclosed. The print bed is heated and has a replaceable polyimide foil layer on the top to help with first layer adhesion. A touch screen is mounted on one side of the printer with a Graphical User Interface (GUI) to interact with the printer, both for maintenance and to set up and run prints.

BigRep ONE Print Process

The BigRep ONE takes advantage of software called Simplify3D, providing a custom profile which allows Simplify3D to operate using BigRep's latest specifications. In order to print a part, the desired STL file is loaded into Simplify3D, the settings are adjusted for both the part and the printer, before the part is sliced into discrete layers and turned into machine instructions called G-code. This is transferred to the BigRep ONE via a local network web server, although users may also use a USB drive with a connection point available on the machine.

Using the onboard touch screen, the operator can then select the desired G-code file for printing from the web server or USB. Initial setup processes such as auto-leveling of the print bed and loading of new filament can also be performed through the GUI. During the print process, data can be monitored such as the temperature of the extruders and print bed, as well as the remaining print time. This workflow of moving from STL file through to printing is identical to most desktop FFF machines, making knowledge transfer for operators who have experience with desktop 3D printing relatively unambiguous.

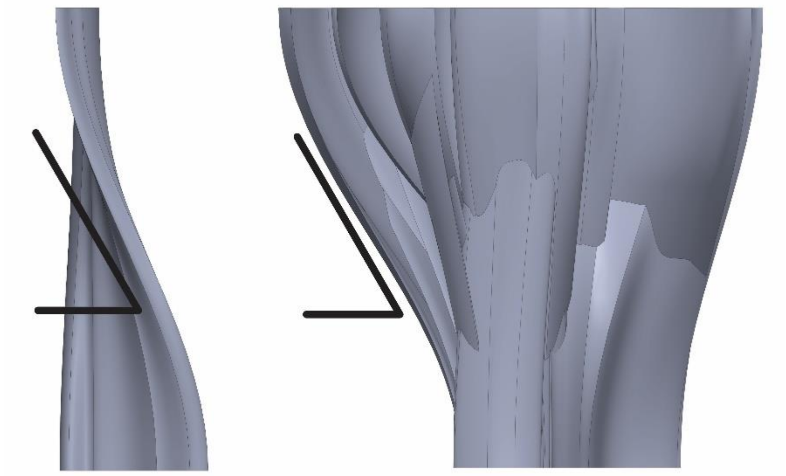
Conceptual Design

The second phase of Kumke et al.'s (2016) framework is conceptual design and the development of basic solution ideas. Guided by the initial design criteria and understanding of the BigRep ONE specifications, a fingerprint concept was chosen as a highly individual element to form the basis of a one-off seating stool. This aligns with recent research into the capacity for AM to enable production of custom products based on personal data or features (Novak, 2018; Rosenkrantz and Louis-Rosenberg 2017). A novel workflow was employed to capture the fingerprint data in a suitable format for the CAD stage: Firstly, impressions were taken from two individuals using ink on paper. These were digitally scanned, before being vectorized using Adobe Illustrator software, and exported as DXF files. The DXF files were imported into Solidworks, a 3D CAD program popular for product design and engineering, where the two fingerprints were spaced 450mm apart and aligned at ninety degrees to each other rather than simply being in the same orientation. This process is represented in Figure 2.

Figure 2. Design process from an ink impression of a finger (left), to a vector tracing in Adobe Illustrator, to the sketches of both fingers imported into Solidworks and spaced apart, to the final 3D model in Solidworks (right)

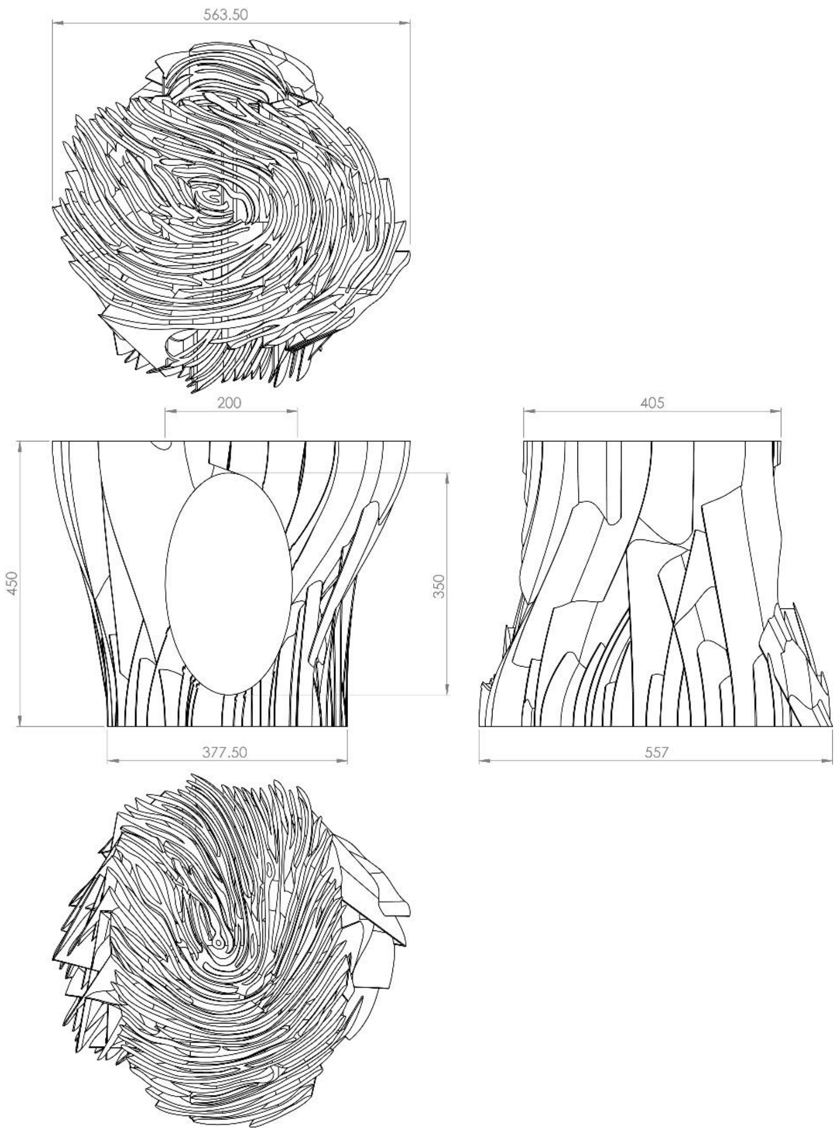
Both qualitative AM design rules, such as build orientation, and more quantitative guidelines, such as support angles, were employed during CAD development in line with Kumke et al.'s (2016) framework. For example, Figure 3 documents some of the early CAD stages with the individual lofting segments of the design maintaining angles ≥60° to safely print without support material, despite similar large FFF studies recommending ≥45° is possible (Urbanic and Hedrick, 2016).

Figure 3. Details of CAD development in Solidworks with loft elements featuring angles ≥60°



Additionally, a flat base was deliberately used so that the stool could be printed on the build plate without a raft or support material. A final notable feature of the design, visible in Figure 4, is the central void cut through the design. After all individual lofts were connected the total volume was $3.73 \times 10^6 mm^3$ despite the numerous internal cavities and voids created through the organic design. Structurally such mass was not required, so an elliptical cavity was extruded through the design, reducing the volume down to $2.56 \times 10^6 mm^3$, representing a reduction of 31.5%. An ellipse was selected due to the shorter unsupported distance compared with a circle, whilst also providing an opportunity to test the BigRep ONE's ability to span a gap without support material.

Figure 4. Overall dimensions of the original design in millimeters



With the BigRep ONE being a scaled-up version of a desktop FFF machine, an initial series of 3D prints were tested on a small desktop machine to learn more about the production of the design at scale, particularly to confirm printability without support material. An example of a 1:6.5 scale model is shown in Figure 5, 3D printed on a 'Wanhao Duplicator i3 Plus' using ABS without support material. After minor modifications to improve results when printed at the full scale, given the overall success of small scale prototyping, this design shifted to the next phase of production through which the primary data of this study was generated. Comparisons between the small-scale prototypes and final BigRep ONE print will be made in the Discussion section of this paper.

Figure 5. 1:6.5 scale model of the initial stool design 3D printed on a Wanhao Duplicator i3 Plus in ABS

Testing, Results and Iteration

The third phase of Kumke et al.'s (2016) framework is the 'embodiment design and detail design,' with simulation being one of the main modules of this phase. Utilizing the ability to simulate 3D printing within Simplify3D, the initial design shown in Figure 4, described as 'Design 1,' was loaded into Simplify 3D with the BigRep ONE profile. Data was gathered about print settings and the effects on cost as the most important metric to the designer (driven by budget), and print time as the most important metric for ProtoSpace (driven by the time the BigRep ONE would be unavailable to other researchers or industry partners). This revealed important relationships between the design and print settings at the large scale of the BigRep ONE, and suggested strategies for the designer to iterate the design to fulfill the design brief. While simulation will not determine if a print will be successful, simulation and prediction are current areas of AM research (Boschetto and Bottini, 2014, Lindgren et al., 2016, Pandit et al., 2017), particularly due to the potential to predict errors and save manufacturers time and money.

Design 1: Simulation

Three settings showing the broad range of outcomes from simulation have been included in Table 2. Some settings remained consistent through testing, for example the infill and number of top/bottom layers, while others were modified in an attempt to reduce print costs and print time. A cost of $150AUD/Kg is charged by ProtoSpace for PLA material on the BigRep ONE, with no additional costs related to print time or setup at this stage. Based on a specified density of 1.3g/cm³ for the BigRep PLA, this equates to a cost of $0.195AUD/cm³. Printing speeds for the BigRep ONE vary in relation to the nozzle diameter and were not modified from the defaults set by BigRep for this testing.

Table 2. Simplify3D settings for Design 1

Setting	Consistent for all tests
Material	PLA
Build plate adhesion	Skirt, no raft
Build plate temperature (°C)	60
No. of top/bottom layers	4
Infill (%)	5
Infill pattern	Grid

	Test 1.1	Test 1.2	Test 1.3
Nozzle Ø (mm)	1	1	2
Number of walls	2	1	1
Layer height (mm)	0.5	0.5	0.8
Print speed (mm/min)	3000	3000	2100
Plastic Weight (g)	20684	14629	25883
Print Volume (cm^3)	15911	11253	19910
Cost ($AUD)	3102	2194	3882
Print Time (hours)	216.1	151	117.5

From the data it is clear that the initial design did not meet the target budget with any combination of settings. Test 1.2 achieved the lowest cost of $2194, which was $694 (46%) over budget. Furthermore, the print time of 151 hours (6.3 days) was considerable, and while not financially measured, was not ideal for the ProtoSpace. The shortest print time possible was Test 1.3 with 117.5 hours (4.9 days); however, this also required the largest amount of material and therefore resulted in the most expensive print method at $3882. The reduced print time is due to the use of a Ø2mm nozzle which prints using a 0.8mm recommended layer height, requiring only 562 layers to produce a 450mm high stool, as opposed to 900 layers with a 0.5mm layer height. While print speed with the Ø2mm nozzle is slower, the significant reduction in layers remains the most important factor determining build time for this part. However, the larger nozzle means more material is deposited everywhere, including the infill, consuming more material and therefore costing more. If the ProtoSpace factored time into the cost equation, the lowest overall cost settings may not be those from Test 1.2, suggesting those adopting large format FFF printing in research centers and industry will need to carefully consider the implications both material costs and time have specific to their circumstances.

Design 2: Iteration

The framework proposed by Kumke et al. (2016) features a “left side bar for iterative forwards and backwards between phases and modules;” design is a dynamic process that necessitates experimentation and the application of new knowledge to progress the design through a cyclical process. Knowledge from phase three simulation was applied back to the phase two conceptual design in the following ways:

1. The overall height of the stool was reduced from 450mm to 420mm. This had the effect of reducing 60 layers of print time if using the 1mm nozzle, or 37 layers for the 2mm nozzle. While reducing height is not always an option for certain design projects, 420mm is still within ergonomic seating standards such as ‘AS/NZS 4688.1:2007 Furniture - Fixed height chairs: Part 1: Human-interface and general requirements’ (Standards Australia, 2007) which specifies a seat height of 410-450mm.
2. The perimeter of the volume was trimmed, retaining the fingerprint concept within a more constrained geometry. Figure 6 provides a comparison between Design 1 and Design 2, with an overall reduction in solid volume of 55.2% ~~and~~ resulting in a final volume of $1.15 \times 10^6 mm^3$.
3. An elliptical perimeter extrusion was added around the elliptical cut-out to provide an end surface for the lofted pieces on the perimeter of the stool, removing potential issues related to unsupported structures. This can be seen in Figure 6.

Figure 6. Render of Design 1 (left) and Design 2 (right)

Design 2: Simulation

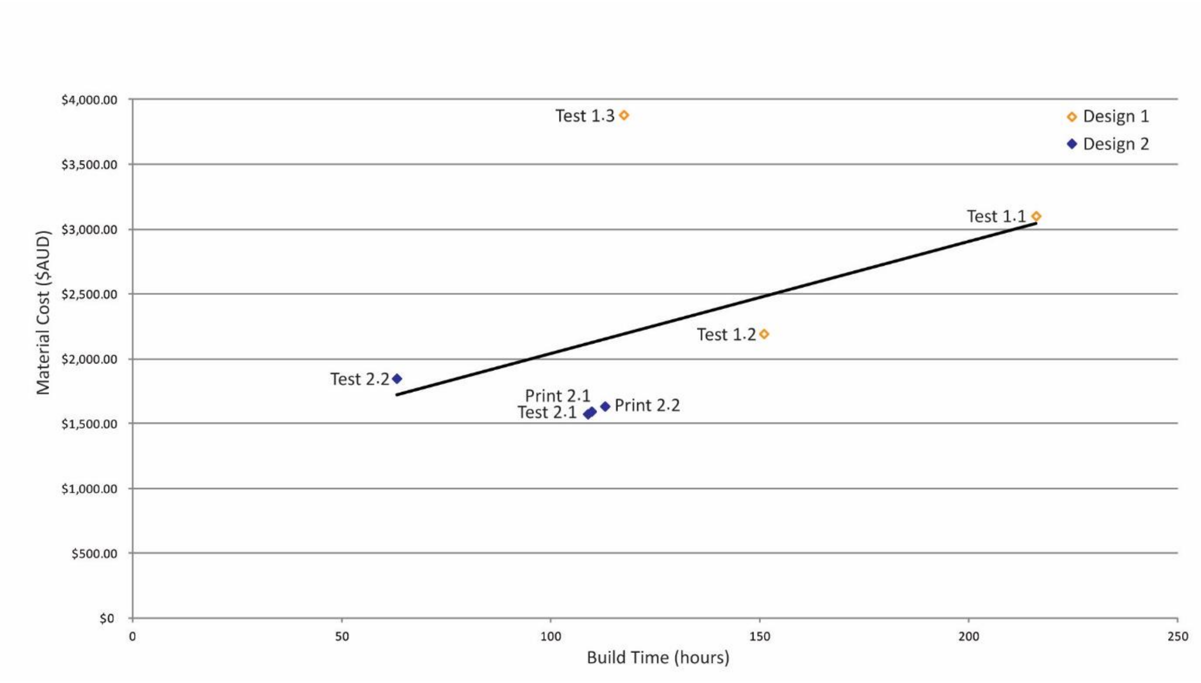
Table 3 lists the results of several simulations with Design 2, two of which were used for final printing on the BigRep ONE.

Table 3. Simplify3D settings for Design 2 – simulations and prints

Setting	Consistent for all tests			
Material	PLA			
Build plate temperature (°C)	60			
No. of top/bottom layers	4			
Infill (%)	5			
Infill pattern	Grid			
	Test 2.1	**Test 2.2**	**Print 2.1**	**Print 2.2**
Build plate adhesion	Skirt	Skirt	Skirt	Raft
Nozzle Ø (mm)	1	2	1	1
Number of walls	2	1	2	2
Layer height (mm)	0.5	0.8	0.5	0.5
Print speed (mm/min)	3000	2100	3000	3000
Plastic Weight (g)	10502	12329	10633	10898
Print Volume (cm^3)	8078	9484	8179	8383
Cost ($AUD)	1575	1849	1595	1634
Print Time (hours)	108.9	63.2	109.8	113

Test 2.1 and Test 2.2 were based on the previous Tests 1.1 and 1.3 to compare the effects of nozzle diameter and layer height on the print time and cost of Design 2. With Design 2 being 55.2% smaller in volume than Design 1, the effect on print time and cost is also roughly half, with Test 2.1 being only $75 over the budget of $1500. A significant observation was the designer's investment in time (5 hours) to modify the CAD file, which resulted in a time saving from Test 1.1 to Test 2.1 of 107.2 hours; in large format 3D printing the application of process control knowledge back into the design through iteration is of measurable value, and time spent in design iteration must be valued by those adopting large 3D printing technologies. With costs within the ProtoSpace being based only on material use, Figure 7 shows the relationships between build time and material cost for both Design 1 and Design 2, with a trend line suggesting a general increase in cost as print time increases. A larger quantity of testing is needed to verify this finding; however, logic suggests that the longer a 3D printer is operating, the more material is being extruded and therefore the greater the cost when no other factors are used in the ProtoSpace cost calculation.

Figure 7. Graph of build time compared with material cost for Design 1 and Design 2



Design 2: 3D Printing

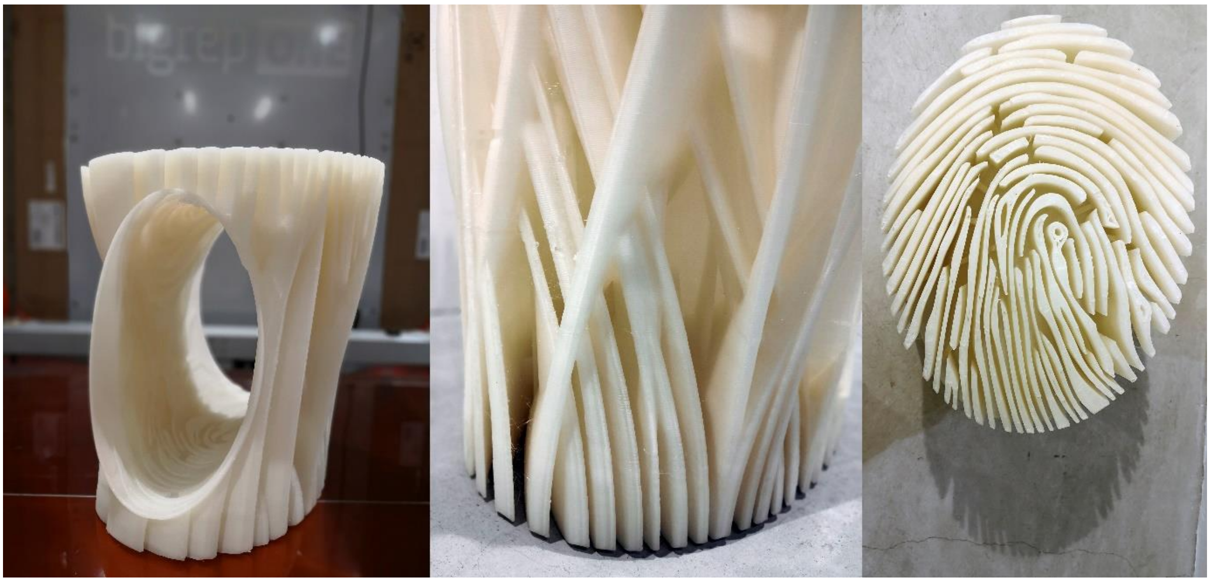
Based on the data in Table 3, Test 2.1 was chosen for 3D printing on the BigRep ONE due to the lower cost and better surface finish compared with Test 2.2 (layer height of 0.5mm compared with 0.8mm). While Test 2.1 would take longer to print, at 108.9 hours (4.5 days) it was still within a working week which was deemed acceptable for the ProtoSpace. As trialed through desktop 3D printing at scale, Print 2.1 was attempted directly on the build plate without a raft; however, numerous attempts failed, with the disjointed pieces of the fingerprint design being easily dislodged if the nozzle collided with them, either through minor warping of the printed pieces, or small discharges of material left sticking up on a surface. Once one of the pieces was dislodged a knock-on effect would cause all pieces to be dislodged as the extruder moved around the build plate.

Figure 8 shows the largest section of print produced with Print 2.1 settings before a dislodged piece became tangled with the extruder, completely entombing it and requiring a new extruder to be purchased. Such problems of warping and build plate adhesion with extrusion-based AM are well documented (Armillotta et al., 2018, Fitzharris et al., 2018, Urbanic and Hedrick, 2016) and commonly seen with small desktop printers, yet due to the small dimensions of materials and parts, errors are often automatically ‘corrected’ without dramatically affecting the overall print. The scale of the BigRep ONE, and the amount of material being extruded, significantly increased the negative effects of errors in printing. Additionally, the polyimide foil on the build plate may not be the most adhesive surface, and the relatively open design of the BigRep ONE with an open top and many gaps around the side doors, may contribute to issues of thermal shrinkage (Singh, 2018). Further research is needed to quantify this hypothesis, and there are plans to enclose the BigRep ONE in the UTS ProtoSpace for future studies.

Figure 8. The largest successful print of Design 2 using Print 2.1 settings

In order to improve build plate adhesion a raft was required along with the settings detailed in Table 3 for Print 2.2. This resulted in a successful print of Design 2, shown in Figure 9. The addition of the raft tied all of the individual pieces of the fingerprint together during the first layers of printing and added three hours and $39 to the print compared with Print 2.1. Some minor warping was observed on the raft, however, because all pieces of the fingerprint were linked together, the combined adhesion force to the build plate withstood any forces of the nozzle colliding with the print, and any distortion was self-corrected as the print built up in vertical height. Raft removal was difficult compared with desktop FFF prints; normally this can be peeled away by hand or with a set of pliers, however, the adhesion between layers, and the amount of material surface area at the large scale, meant that this was impossible. A hammer and chisel was found to be the most effective method to slice between the layers of the raft and printed stool, a process that took approximately one hour. Therefore, overall production time for the stool can be adjusted to 114 hours. An alternative would be to use a large bandsaw, however, due to the organic geometry of the stool, laying it on the side and cutting off the raft would be dangerous and may require the creation of a jig to keep it in position. The final surface where raft was removed is not as smooth as the top surface due to this process.

Figure 9. Final result of Design 2 using Print 2.2 settings



Metrology

Overall dimensions from the final print were collected and compared to the original CAD file to quantify the accuracy and calibration of the BigRep ONE. A Mitutoyo LH-600E linear height system was used, featuring an accuracy of ±0.001mm when coupled with an accurate flat surface. Figure 10 illustrates the orientation of the X and Y axes, with the Y axis in line with the elliptical cut-out through the stool. The process of capturing the Z axis measurement with the linear height system is also shown. For the Z axis, two measurements were taken at either end of the X axis to check for consistency across the vertical print orientation. The overall dimensions were compared with measurements of the STL file in the same locations, and the dimensions of the elliptical cut-out were also recorded. This data is shown in Table 4.

Figure 10. Measurement axes of the stool and detail of the Mitutoyo LH-600E linear height system measuring the Z-axis

Table 4. Physical dimensions compared with STL dimensions

Axis	**Real** (±0.001mm)	**CAD** (±0.001mm)	**Difference** (mm)	**% Difference**
Overall				
X	390.652	390.338	0.314	0.080
Y	298.270	297.842	0.428	0.144
Z (Left)	417.615	417.434	0.181	0.043
Z (Right)	420.567	420.914	-0.347	-0.082
Cut-out				
X	187.971	187.331	0.640	0.342
Y	304.618	304.675	-0.057	-0.019
Z	319.634	319.712	-0.078	-0.024

Metrology data revealed an overall variation between the digital STL file and physical print of ≤0.64mm or ≤0.342%, a suitable result for a singular piece of furniture that does not need to interface with other components. For comparison, a study by Lieneke et al. (2016) found a maximum deviation for sample parts of 0.5mm on a Fortus 400mc machine from Stratasys with a 400mm sample length. This shows a good accuracy for the BigRep ONE given the features of a Fortus 400mc machine which include an enclosed and heated build chamber, and may be attributed to the recent installation of the BigRep ONE at the time of the project and calibration as part of this setup process. It is possible that accuracy will change over time and between calibration routines, and such testing would form part of future research.

Surface roughness of the stool was also recorded using a Mitutoyo SJ-210 portable surface roughness tester, which conforms to ISO 4287:1997. Similar hand-held equipment has been used in studies of FFF surface characteristics (Pérez, 2002, Reddy et al., 2018). A Gaussian cut-off filter was used to evaluate surface parameters, and an evaluation length of 12.5mm at three locations was used as shown in Figure 11. These surface locations were chosen as they lack major design features. A cut-off length of 2.5mm was used for 5 (N) samples at each location (5 × 2.5mm = 12.5mm), and a stylus speed of 1mm/s was used perpendicular to the layers. Results for each sample and averages are shown in Table 5.

Figure 11. Surface locations of the stool sampled for surface roughness

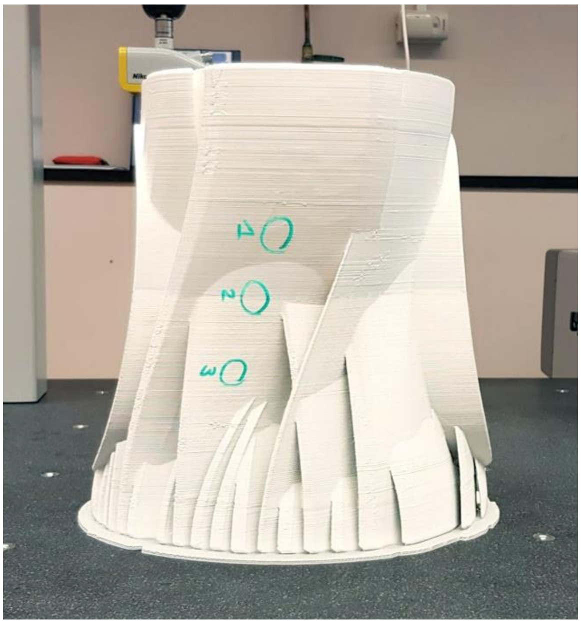


Table 5. Surface properties of the stool in accordance with ISO 4287:1997

Sample	**1** (μm)	**2** (μm)	**3** (μm)	**Average** (μm)
Ra	38.241	37.238	37.689	37.723
Rq	45.846	44.722	44.802	45.123
Rp	58.072	53.756	52.925	54.918
Rv	117.84	117.63	111.48	115.65
Rc	161.58	153.33	153.67	156.19
Rt	200.50	186.64	183.26	190.13

As expected, surface roughness values, particularly R_a which is the most common comparative value (Todhunter et al. 2017), are greater than studies conducted using other FFF hardware that has typically focused on more accurate processes with layer heights <0.254mm (Kim and Oh, 2008, Lieneke et al. 2016). While the data collected in this study requires validation through more specific surface roughness testing, it can be used as an initial benchmark for future studies on the BigRep ONE and other large area additive manufacturing equipment which is currently lacking within academia.

Discussion

Comparing the final Print 2.2 produced on the BigRep ONE with smaller desktop printed prototypes, the negative effects noticed at the desktop scale were typically scaled up and exaggerated at the full scale. Table ~~4~~ 6 presents observations.

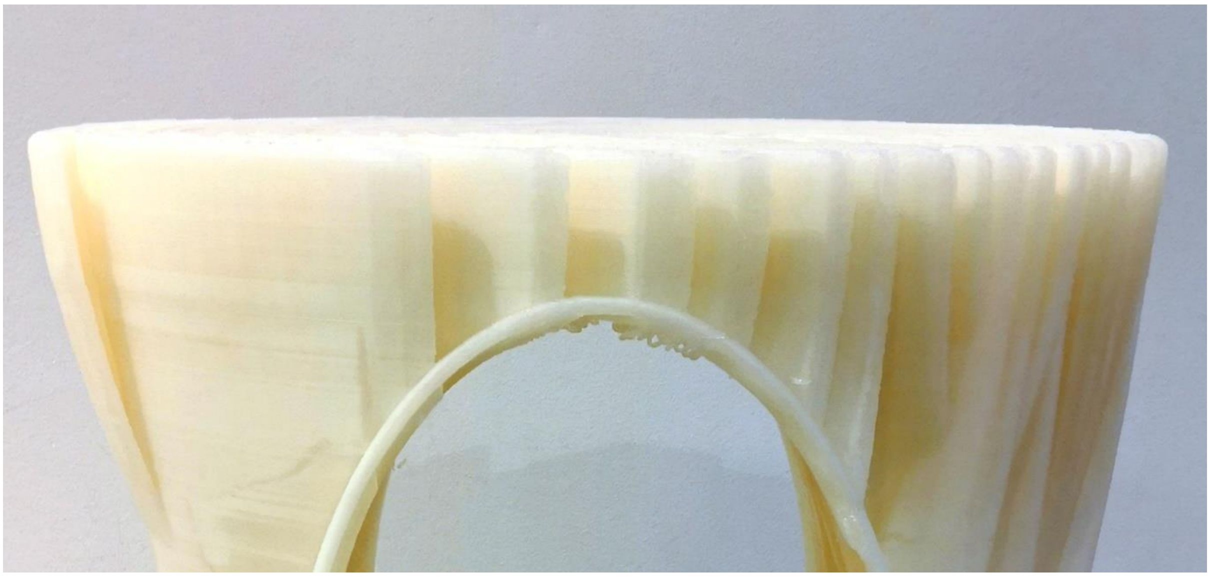
Table ~~4~~6. Comparison of desktop FFF 3D printing with the BigRep ONE

Observation	Desktop FFF	BigRep ONE
Material volume/cost	Modifications to settings will vary material costs in the region of tens of dollars.	Modifications to settings will vary material costs in the region of thousands of dollars (e.g. Design 1 = $2194-3882).
Print time	Scale models took in the range of 7 (Design 2) to 14 (Design 1) hours. For desktop 3D printing, prints over 24 hours in length are uncommon.	Modifications to settings can vary print times by over 100 hours (Design 1). This is a significant time for a piece of equipment to be unavailable for other projects.
Base warping	Normally an issue with ABS due to the stresses caused by shrinkage as the molten polymer cools (Armillotta et al., 2018), however, the print will often continue and self-correct. Rafts were unnecessary in prototyping.	Warping can be catastrophic due to the scale of parts – in this study warping would completely dislodge a part from the build plate and cause collisions with the nozzle. A raft was needed.
Surface finish	0.2mm layer height of prototypes is noticeable on close observation.	0.5mm layer height is noticeable from a distance and is a tangible feature when interacting with the stool. Surface roughness data quantifies this.
Unsupported areas e.g. underside of ellipse	Messy extrusion can normally be removed by hand or hand tools.	Messy extrusion becomes a feature of the product due to the amount of material and difficulty in removing it. Power tools may be required for post-processing.
Layer splitting	ABS shrinkage can cause layers to split apart, and may affect functional strength.	No splitting between layers observed.

The warping of the ABS scale prototype, which was visually noticeable but not enough to affect the printing process, became a major problem during Print 2.1 attempts, with warping and low build plate adhesion causing failure of printing. For Print 2.2, it is therefore surprising that the final outcome achieves good tolerances to the CAD data, evidencing an ability to self-correct as layers build in the vertical orientation. Layer splitting is not a noticeable issue in the final print, most likely because it is PLA and not as prone to shrinkage as ABS, however, as shown in Figure ~~10~~12, the stair-stepping effect is an obvious detail, as are irregularities in the extrusion bead, small gaps of missing infill, and stringing caused by the nozzle moving between sections of the printing layer. Such details can be seen on close inspection of desktop FFF prints and become exaggerated at the larger scale (Duty et al., 2017). For designers this surface finish must be considered as part of the design and may require post-processing with additional time and financial costs. The surface roughness data recorded for the stool may be used to benchmark other additive manufacturing processes where surface roughness is an important factor. The underside of the elliptical cutout also features the same messy detail of the small-scale prototype at a larger scale, as shown in Figure ~~11~~13, but did not affect printing. Further modifications of print settings, such as print speed and material flow, as well as use of a smaller Ø0.6mm nozzle available for the BigRep ONE, may improve surface results, however, will affect print time.

Figure ~~10~~12. Detail of stair-stepping on Design 2 (produced as a secondary print in white PLA)

Figure ~~11~~13. Detail of the underside of the elliptical cutout of Design 2



Limitations and Future Work

From a software and simulation perspective, the settings trialed during this study are a relatively small set based on the defaults recommended by BigRep, and do not capture the quantity of possible adjustments within Simplify3D. This is due to the machine being only newly installed within ProtoSpace, with technicians using projects such as this to develop an understanding of machine capabilities. Given the appearance of a trend for costs to increase as print time increases, more data is needed to verify this trend and explore the full range of possible settings that will affect the slope of the trend line. Outliers such as the high cost and low print time for Test 1.3 need further investigation to explore the settings around them, and may be useful settings for service bureaus and manufacturers to offer short turnaround options for clients willing to pay the resulting higher cost. At the opposite end of the spectrum, highly detailed settings with small print nozzles <Ø1mm were not trialed in this study, and while the data suggests print times will be slower than those recorded, it is important to know by what factor for certain projects where detail and surface finish are of a higher priority.

From a hardware perspective, the BigRep ONE was treated like a single extruder machine in this study due to the desire to print without support material, which is often the main application of a second extruder. However, it may be beneficial to experiment with two different sized nozzles to optimize printing speed and material use, for example using a fine Ø0.6mm nozzle for the perimeter for increased surface quality, and a thicker nozzle to add strength through the interior in a shorter time as proposed in previous literature (Sabourin et al., 1997). Additional studies need to consider the effects of the relatively open design of the BigRep ONE within an air-conditioned space like the ProtoSpace, and whether enclosing the build volume reduces thermal shrinkage and warping of parts, potentially improving adhesion to the build plate. Additional heating of the build chamber may also need to be considered, as well as experimentation with different build plate materials or adhesives to improve adhesion of the first layer based on previous studies (Singh, 2018). This could extend to characterization of the rheology of the PLA filament, which recent research has shown to vary in composition between brands and colors, affecting the ability to produce parts (Cicala et al., 2018). Ideally the fingerprint stool should be printed without the raft as it has been specifically designed with a flat surface to adhere to the build plate, and therefore no waste or post-processing would be required. Novel research is being developed for BAAM technology to help resolve these concerns with large FFF 3D printing (Kishore et al., 2017, MacDonald et al., 2017), and may be suitable for deployment on the BigRep ONE.

While metrology data has been gathered for the stool, including overall dimensional accuracy and surface roughness, it is important to note that given the complex organic form, and the production of a single part, the data requires validation through more specific testing following standardized and replicable procedures. Such detailed knowledge of the BigRep ONE was not the aim of this study, and measurement data was challenging due to the complex curved surfaces. This has lead the authors to conclude that the DfAM methodology provides some limitations to the knowledge gained of a particular AM process dependent on the complexity of the design.

Conclusion

Returning to the initial criteria for this study, the stool exemplifies what can be achieved with a large area FFF printer, yet also highlights the challenges of working at large scales:

1. The final design was $134 over the initial budget. $39 of this is attributed to the necessity for a raft. This is within 10% of the proposed $1500 budget. Failed prints were not charged by ProtoSpace but must be considered by printing bureaus and research centers acquiring a BigRep ONE or similarly emerging technology.
2. A print time of 4.7 days (113 hours) was achieved, meaning the printer was only unavailable for a single working week.
3. The stool is a one-off, custom design featuring fingerprints captured using a process of traditional and digital means, and demonstrates how to design specifically for AM.
4. The internal complexities as two different fingerprints merge together could not be manufactured using traditional technologies.

5. The stool is functional and within ergonomic seating requirements at 420mm tall.
6. No support material was needed. However, a raft was found to be necessary to improve adhesion to the build plate. Further research into build plate materials and enclosure of the BigRep ONE is needed to eliminate this waste material and post-processing time.

As an exemplar, the knowledge gained through the process of design and testing is embodied in the final product, and will help demonstrate to academics and industry the potential of using the BigRep ONE and similar large area Fused Filament Fabrication machines.

Following a Design for Additive Manufacturing framework, this study has resulted in a new understanding of the relationships between print settings, material costs, print time and design for large area FFF. While numerous studies have explored the technical aspects of this technological at desktop to Big Area Additive Manufacturing (BAAM) scales, the recently released BigRep ONE printer has not been featured in peer reviewed studies. With a price-point in the tens of thousands of dollars, it may be an attractive addition to manufacturing, engineering, prototyping and design facilities and requires new research about the opportunities and limitations in relation to similar large scale FFF printers, as well as smaller scale desktop printers. Simultaneously, as additive manufacturing increasingly shifts from a prototyping to end-use production technology, it is necessary for design engineering to develop new workflows and processes for engaging with emerging print technologies, drawing upon prior experience and learning through a process of creating and making.

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