



DEMOCRATISATION OF DESIGN FOR FUNCTIONAL OBJECTS MANUFACTURED BY FUSED DEPOSITION MODELLING (FDM): LESSONS FROM THE DESIGN OF THREE EVERYDAY ARTEFACTS

Goudswaard, Mark; Hicks, Ben; Gopsill, James; Nassehi, Aydin
University of Bristol, United Kingdom

Abstract

The purpose of this paper is to explore how the democratisation of design can be achieved for useful items manufactured by Filament Deposition Modelling (FDM). This is achieved through a design study that involves the identification of typical functional objects manufactured by FDM and then performing and mapping the design process for these items. Through analysis of the respective difficulties contributed by different categories of actions, four areas of the design process are identified as requiring improvement in order to democratise design. The study also finds that it is easier to amend models than it is to generate them from scratch. This leads to the consideration of democratising design through amending existing models in design repositories, such as Thingiverse. The discussion examines the consequences of these findings and how they impact the requirements and possible functionality of a system that could meet the challenge of democratising FDM design.

Keywords: 3D printing, Case study, Collaborative design, Democratisation of design

Contact:

Mark Andrew Goudswaard
University of Bristol
Mechanical Engineering
United Kingdom
mark.goudswaard@bristol.ac.uk

Please cite this paper as:

Surnames, Initials: *Title of paper*. In: Proceedings of the 21st International Conference on Engineering Design (ICED17), Vol. 5: Design for X, Design to X, Vancouver, Canada, 21.-25.08.2017.

1 INTRODUCTION

Fused Deposition Modelling (FDM) is a ubiquitous additive manufacturing technology that is widely used by consumers and hobbyists to create a wide variety of both novelty and functional parts and components (Wittbrodt et al., 2013). Because of the versatility and affordability of FDM machines, they can allow people to cheaply and easily build complex and useful items. As a result FDM is a forerunner in the democratisation of manufacture (Robinson, 2014) – bringing production to the masses and empowering individuals to make things themselves, in their own homes and communities. This also has a significant sustainability benefit as additive manufacturing has the potential significantly lower the life cycle energy demands and CO2 emissions of goods by reducing tooling requirements, material wastage and supply chain lengths (Gebler et al., 2014).

To date, there are two main processes (depicted in Figure 1) that one can take to design and manufacture components using FDM. The first involves the design of the component using 3-dimensional geometric tools such as Computer Aided Design (CAD). From this, a stereolithography (STL) file is produced and imported into the Computer Aided Manufacture (CAM) software to produce the G-Code instruction set for the FDM machine. Thus, to follow this process, individuals require considerable engineering knowledge to produce a component. This has been noted as a key barrier to entry of 3D printing in industry (McCutcheon et al., 2014), small and medium enterprises (Conner et al., 2015) and as a key barrier to their uptake in developing countries (Birtchnell and Hoyle, 2014) as well as an area of work identified in the initial findings for the UK's strategy for additive manufacturing (Dickens and Minshall, 2015).

To overcome this limitation and democratise the design and manufacture process for FDM machines, the second process involves individuals downloading models from design repositories, which contain thousands of template models. These can be either immediately submitted to the FDM machine for manufacture or are imported into the CAM software. Thingiverse is one such example, which typically sees 1.7 million downloads a month (Watkin, 2015). Although their utility has been demonstrated, the repositories represent a highly-constrained design environment where an individual has limited to no opportunity to modify or further develop a model.

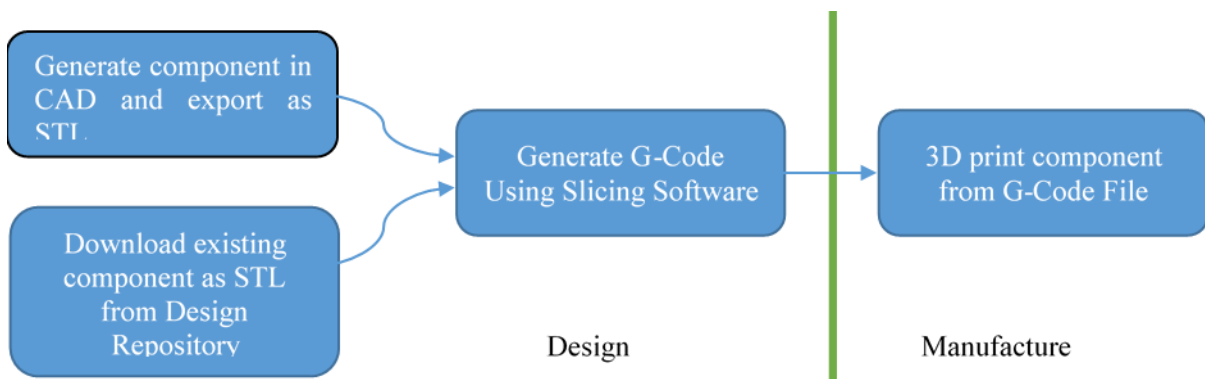


Figure 1. Workflows for manufacture through FDM

Given that there are many areas that could be further supported or improved in the FDM design process there is a need to understand which elements if improved, would have the greatest impact for democratising design. To investigate this, this paper seeks to understand:

- The common design tasks carried out with FDM and elucidate the fundamental design challenges that need to be overcome.
- The underlying design process followed to produce useful parts with FDM.
- The steps in the design process that contribute most to the level of difficulty and hence act as barriers to the democratisation of design.
- Whether it is the technical ability or understanding of the individual that needs to be supported in order to democratise design.

The results of this study provide the basis for a discussion of the challenges, requirements and opportunities for democratising design capability in the context of 3D printing. The paper concludes with a discussion of areas for future work.

2 TYPES OF DESIGN TASKS FOR 3D PRINTING

In order to further support the democratisation of design using FDM, an understanding of the types of design problem individuals are trying to address is required as this heavily influences the types of design task/activity that the individual would wish to perform. To investigate this, this paper has analysed the 81 most popular items on Thingiverse (MakerBot, 2016). These products have then been categorised against:

- Whether they are functional or novel. Examples of functional items included a G-clamp, lamps, a Raspberry Pi Case and parametric nuts and bolts. Novelty items included a Millennium Falcon, spinning top and an Iron Man suit. Whilst FDM is a powerful manufacturing tool, it is thought to be largely used to make models and trinkets! This categorisation will allow the proportion of functional items to be identified, as well as distinguishing the design problems faced by functional and novelty items respectively.
- The principle design problem that need to be overcome. These are explored in greater detail in Table 1. If an item consisted of additional parts that were not all 3D printed, the design problem was assigned with respect to the 3D printed parts.

Additional information taken from the design repository included total downloads and date added in order to create a normalised metric of downloads per month which would allow a comparison of popularity across the items.

Table 1. Design mode definitions

Design Problem	Definition	Example
Fit/Interface	Limits, fits and interfaces. How a component interacts with another topologically.	<ol style="list-style-type: none"> 1. G-Clamp – operation is determined by a thread. 2. Raspberry Pi case – requires the components to fit together.
Load	The way an object responds to load. This could be to resist breaking under a given load or to deflect a certain amount.	<ol style="list-style-type: none"> 1. G-Clamp – needs to provide a specific clamping force. 2. Spray can holder must be able to hold weight of can. 3. Parametric pulley must be strong enough to transfer a given load.
Size	How a component interacts with another on a macro scale.	<ol style="list-style-type: none"> 1. Lamp Shade must be of correct size to contain light fitting. 2. Raspberry Pi case must be correct size to fit Raspberry Pi. 3. Bottle Cap must be appropriately sized for a particular bottle. 4. Mask must be appropriately sized to fit on a face.
Functional Shape	How a component's shape affects its function (behaviour). This is not form, as all of the design modes listed will result in change to the form of the object.	<ol style="list-style-type: none"> 1. Spinning top shape alters its inertia and ability to spin. 2. Vacuum cleaner adaptor changes the airflow. 3. Sundial blocks light to show the time.
Aesthetic Shape	How a component appears aesthetically.	<ol style="list-style-type: none"> 1. Iron Man suit needs to look like Iron Man. 2. Vase must look good to complement its contents.
Mass	When variations in a components mass can alter its behaviour. This is important with 3D printing as infill and shells are variable.	<ol style="list-style-type: none"> 1. Quadcopter chassis must be light enough to fly. 2. Mass and distribution of mass of a spinning top will alter its ability to spin.

The design challenges were defined based on the list item surveyed. Whilst there are arguably more that could be assigned to 3D printed parts, for example thermal insulation. These six categories were deemed to be satisfactory as they were able to categorise all items in the survey. The key design challenges along with examples are presented in Table 1.

Items were all categorised according to the two principle design challenges faced in their design, except for a few novelty items whose sole design objective was that of aesthetic shape. All of the design modes result in alterations being made to the form of the item.

2.1 Results

Of the 81 items surveyed, 24 were ‘novelty’ and 57 ‘functional’ corresponding to 70% being functional. When the items were normalised with respect to downloads per month, 61% percent of the 169,000 monthly downloads were for functional items.

Figure 2 shows how the design challenges vary as a percentage of total downloads per month for the surveyed items and also separately for functional and novelty items. From Figure 2, it can be concluded that the most important design mode for novelty items is (perhaps unsurprisingly) aesthetic shape and secondly fit. For functional items, the crucial design problems are identified as fit, load and size. Combined they account for over 75% of the design modes identified.

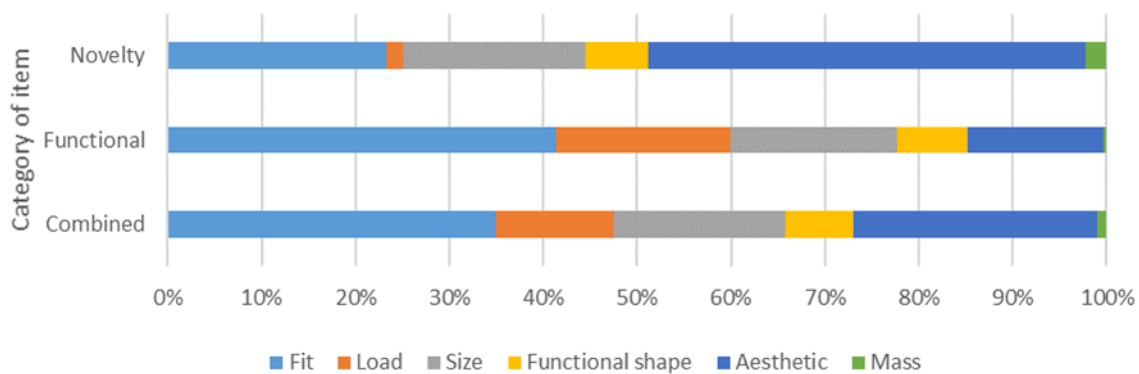


Figure 2. Distribution of principle design modes of the surveyed items



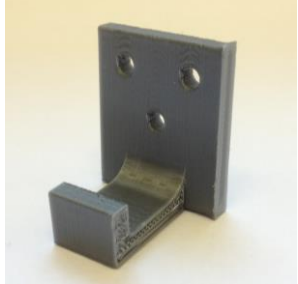
2.2 Conclusions

The key design problems for 3D printed items have been identified for the items surveyed as a total and also when broken down into functional and novelty categories. In democratising design and manufacture we are concerned with the manufacture of useful items. Therefore, the design problems we are most interested in are those associated with functional items. As a result, the following section examines the design process in detail for the design of a series of 3D printed components for the tasks of fit, size and load.

3 3D PRINTING DESIGN PROCESSES

Using the most common design problems identified in Section 2, the study continued by looking at the activities that an individual would take in order to solve them. This was performed by the primary author who is proficient in 3D printing methods & technology (having designed and built a 3D printer (Goudswaard et al., 2017)) and engineering holding an MEng in Mechanical Engineering. The studies focussed on functional items defined by the design problems of fit and size, the second of fit and load and the third on load and size. The items designed are explained and depicted in Table 2. The first aim of these studies is to examine the nature and number of design steps (actions) undertaken. The design tasks were iterative and modelled from scratch using Autodesk Inventor 2016. Each item had a set design goal that had a simple pass / fail criterion. This is included in Table 2. After each iteration, the item was printed and tested with a decision made to whether it met the requirements and on the design strategy if it required improving.

Table 2. Case study overview

	<i>Fit and Size</i>	<i>Fit and Load</i>	<i>Load and Size</i>
Object	Bottle Cap	Table hanger	Coat Hook
Explanation	Design challenges are fit of thread and size to fit specific bottle	Object is required to withstand a given load, and fit onto the table edge	Required to hold a given load applied by an item of given size
Success criteria	Successfully prevent leakage from a bottle	Hold load of 20kg	Hold load of 20kg
Picture			

Various methods were considered for the logging of steps during the design process. An Issue Based Information System (IBIS) approach was considered though was disregarded as it would not permit a clear way to present and analyse the information (Noble and Rittel, 1988). Integrated Definition Model (IDEF) protocols were also considered but no existing framework existed that could capture the level of detail required (KBSI, 2016). Protocol analysis techniques were also examined though these were more concerned with creative and complex design tasks whereas we are more concerned with the individual, small scale processes and decisions which permit the design of what is arguably a very simple object (Cross et al., 1996).

As no existing method was found that could adequately capture the required data it was decided that a spreadsheet would be the best method to capture information during design. Table 3 shows the information that was recorded during each task along with some sample rows to demonstrate the manner in which information was recorded.

Post design task, further columns in the spreadsheet were then populated. These were not filled in at the time of design so as to minimise disruption to the process. These can be seen in Table 4. The steps were then categorised into five categories that corresponded to areas of the design process where democratisation could occur:

- **Software Interaction** – e.g. opening a program, saving a part or exporting a file.
- **Hardware Interaction** – e.g. operating a 3D printer.
- **Decision** – e.g. choosing a course of action, deciding how to use the software to achieve a goal.
- **Observation/Measurement** – e.g. testing an item or identifying features on an existing object.
- **Geometry alteration** – generating or changing 2D or 3D geometry.

Table 3. Extract from Case Study 1 to demonstrate recorded information during design

Action number	Action	Computer Interaction	Inspection of part	Issue	Options	Decision	Justification	Information/Data
1		Open Inventor						
2		Generate New Part						
3			Inspect Existing cap to identify features					1) Female Thread 2) Textured edge to allow gripping 3) Tapered open end of cap to allow placement
7				How to model bottle cap?	1) First model cylinder then subtract another cylinder of material from inside 2) Revolve a 2D sketch to make cap shape	1	Easiest way to model cap, easy to modify as well	

Table 4. Extract from case study 1 to demonstrate information recorded post design task

Action number	Outcome	Category of outcome	Depth of knowledge required	Technical Ability	Technical Understanding
1	Inventor open	Software operation	Low	1	0
2	New part generated	Software operation	Low	1	0
3	Features identified	Observation	Be able to identify thread and the purpose of the textured edge	1	3
7	Decision made for design strategy to model cap	Decision	CAD knowledge of options to generate the required shape, and make a reasoned decision to which is the best method	4	0

3.1 Results

Figure 3 shows the cumulative number of steps for each design process broken down into the various categories.

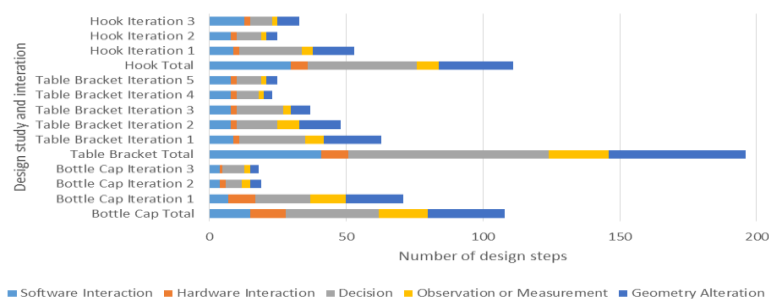


Figure 3. Number of design steps for each case study and iteration

3.2 Concluding remarks

The types of design steps when designing for 3D printing have been identified as software interaction, hardware interaction, decisions, observations/measurements and geometry alteration.

From Figure 3 we can conclude that:

- Generating geometry requires more steps than altering geometry.
- Decisions account for the majority of steps in all studies and iterations.
- Observations and measurements greater in geometry generation than in subsequent iterations.
- Number of hardware and software steps remain consistent across iterations as would be expected as there are a set number of steps associated with saving/opening files, exporting STLs setting parameters and printing. Variation step by step will therefore be in the proportions of decisions, observations and measurements and geometry alterations.

4 WHICH PROCESS IS THE MOST DIFFICULT?

To investigate the most challenging step for the hobbyist/consumer, the three case studies were further post processed to consider the level of technical complexity of each design step.

Difficulties from 0-5 were assigned for each design step with respect to technical ability (A) and technical understanding (U). Ability encompassed difficulties associated with use of the software and hardware. Understanding encompassed broader knowledge tailored towards the function and behaviour of the item. For example, deciding to add a fillet to reduce stress concentrations requires technical understanding whereas amending the model to add a fillet requires technical ability. It is important to distinguish between these as it is likely that democratisation of one would require very different interventions to the other. The difficulties assigned along with explanations for levels along with examples are shown in Table 5.

The difficulties were then totalled in order to give a value that represented the technical ability or understanding required to complete a given iteration. This could then be split further to see what category of step (e.g. decisions) contributes most to the difficulty of the design process.

Table 5. Definitions of defined difficulties

Difficulty	Description	Technical Ability Example	Technical Understanding Example
0	Not relevant to task		Change a dimension
1	Requires everyday knowledge	Open Autodesk Inventor	Identify what bracket needs to fit to
2	-	Open existing sketch	How will a hook hang an item?
3	Requires technical knowledge that could be learned through hands on experience	Apply Fillet to corner	Identify measurements that are required for design.
4	-	Use Inventor offset function	Decide shape profile to minimise stress concentrations
5	Requires knowledge that was taught in engineering degree	Edit thread profile to better suit requirements	Decide design strategy to reduce deflection under load

4.1 Results

Figure 4 shows the totals of technical ability and understanding for each design task as total and also broken down by iteration. Table 6 **Error! Reference source not found.** shows a heat map of the average difficulties of:

- All processes for:
 - each design task's total iterations
 - individual iterations
- Individual design categories
 - each design task's total iterations
 - individual iterations

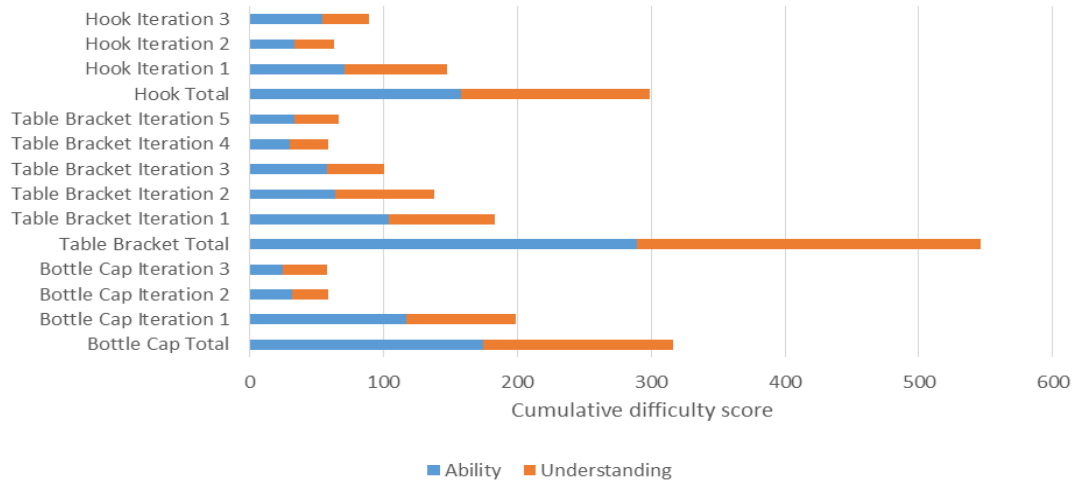


Figure 4. Difficulty scores for ability and understanding

Table 6. Areas of relative difficulty in the design process (Ability (A), Understanding (U))

		Software Interaction		Hardware Interaction		Observation & measurement		Decision		Geometry		TOTAL	
		A	U	A	U	A	U	A	U	A	U	A	U
Bottle Cap	Iteration 1	1.7	0.0	2.0	0.0	1.6	3.2	3.3	2.9	3.2	2.0	2.7	3.0
	Iteration 2	1.8	0.0	2.0	0.0	2.0	2.3	5.0	4.0	3.0	0.0	2.5	3.4
	Iteration 3	1.8	0.0	2.0	0.0	2.0	4.0	3.0	3.6	3.0	0.0	2.3	3.7
	Cap Total	1.7	0.0	2.0	0.0	1.7	3.2	3.4	3.3	3.1	2.0	2.6	3.2
Table Bracket (TB)	Iteration 1	1.7	0.0	2.0	0.0	2.2	3.0	3.5	3.1	2.9	0.0	2.5	3.0
	Iteration 2	1.8	0.0	2.0	0.0	2.3	3.3	3.0	3.7	2.2	0.0	2.1	3.5
	Iteration 3	1.8	0.0	2.0	0.0	2.0	2.7	2.8	3.1	2.7	0.0	2.3	3.0
	Iteration 4	1.8	0.0	2.0	0.0	3.0	3.0	3.0	3.3	2.0	0.0	2.0	3.2
	Iteration 5	1.8	0.0	2.0	0.0	3.0	3.0	3.0	3.4	2.3	0.0	2.1	3.3
	TB Total	1.7	0.0	2.0	0.0	2.3	3.0	3.1	3.3	2.5	0.0	2.3	3.2
Hook	Iteration 1	1.7	0.0	2.0	0.0	1.5	3.0	3.0	3.2	2.5	0.0	2.2	3.2
	Iteration 2	1.8	0.0	2.0	0.0	1.5	2.5	3.0	3.6	1.5	0.0	1.8	3.3
	Iteration 3	1.8	3.0	2.0	0.0	2.0	3.0	3.0	3.3	2.5	3.0	2.1	3.2
	Hook Total	1.7	3.0	2.0	0.0	1.7	2.9	3.0	3.3	2.3	3.0	2.1	3.2

4.2 Concluding remarks

From Figure 4 it can be concluded that for the different design problems and across different design iterations the split of total difficulty is fairly equal for understanding and ability. Average for understanding is consistently higher than that of ability. Suggesting that the greatest difficulty in design is not in the use of specialist software but the background knowledge of how items function.

Table 6 identifies four categories that consistently provide difficulty:

- **Understanding of observation and measurement** - e.g. knowing what to look for or measure.
- **Technical ability based decisions** - e.g. reasoning on which functions to use to achieve a given goal.
- **Technical understanding based decisions** - e.g. how change/modify a structure to reduce stress concentrations.
- **Technical ability to amend geometry** - using the software to achieve a given goal.

From Figure 4 we can also conclude that generating geometry (iteration 1) is more complex than editing geometry (subsequent iterations) and Table 6 shows that the average total difficulty per design iteration remains fairly consistent.

5 DISCUSSION AND FUTURE WORK

The aim of this paper was to explore the design processes of functional parts manufactured through FDM with a view to facilitating democratisation of design. This was achieved through consideration of four research questions.

The first identified the common items manufactured by FDM and elucidated the fundamental design problems that need to be overcome in their design. It was found that 61% of items by download count were functional, revealing that manufacturing of useful parts via FDM is already significant and that the proposition of democratising design via FDM is valid. The principal design problems of FDM items were found to be fit, load and size.

The second research question mapped the underlying design process followed to produce useful parts with FDM. The steps taken were categorised in order to understand the types and quantities of tasks undertaken during the design process. This allowed a comparison of the design steps taken between the different design tasks and design iterations. It was found that it takes fewer steps to amend geometry than it does to generate geometry suggesting that amending existing models from design repositories would be an easier and more efficient means to generate functional models than designing from scratch. The final two research questions sought to identify the steps in the design process that contribute most to the level of difficulty and thus potential challenges for democratisation. In particular, technical ability and technical understanding were evaluated in order to examine the relative levels of proficiency required. The areas contributing most to the level of difficulty were found to be technical understanding for observations and measurements, technical ability and understanding for decision making and technical ability for amending geometry. These therefore represent the key areas that need to be addressed in or to democratise design, which might include for example one or a blend of automation, semi-automation, crowd sharing or out-sourcing.

With respect to the average difficulty of design step, understanding is the more challenging issue occurring in more categories than ability, however, cumulatively the contribution to total difficulty is relatively equally split between ability and understanding. The consequences of this are twofold. First, it is necessary to determine whether it is more beneficial to remove many of the easy steps from the design process or eliminate/recue the difficulty of a smaller number of more challenging steps. This will depend largely on the user group that we are democratising design for and would result in either a system that follows the instructions of the user, or on the contrary, tells the user what to do. Secondly, given that understanding is the more challenging issue across a greater number of categories, creating user-friendly tools is not sufficient to truly democratise design. There needs to be guidance in the decision-making process, meaning a tool would need to understand how changes in a parts behaviour or function can be brought about by alterations to its geometry.

Any system that is developed to democratise design will need to exploit the strengths of both the human and computer in order to effectively co-design parts. More general information will need to be provided by the user – the computer can then generate more complex parts of the design, requesting information such as measurements from the user when necessary.

Any system developed would require substantial knowledge bases in order to function effectively. It would likely need to be able to identify features on a model in order to ascertain which are key to its function. It would also need to know a large number of constraints manufacturing constraints in order to define its design strategy such as design time, print time and material available. It would also need to understand general design rules for FDM such as designing without overhangs and how to orientate a part when printing so as to achieve optimum material characteristics.

Many avenues for further work have been identified however in the short term further work will focus on:

- Further study to expand and validate the results presented in this paper.
- Comparative study investigating the sensitivity of the potential democratised design process(es) to levels of automation, semi-automation, crowd sharing or out-sourcing for example.
- Strategies for democratising and their relative knowledge-based requirements.

6 CONCLUSION

This paper has presented a study that has identified areas in the design process for FDM that if improved would facilitate the democratisation of design. These were found to be: technical understanding to make

observations and measurements; technical ability and understanding to make design decisions; and, technical ability to amend geometry. In addition to this, the study found that the principle design problems of objects typically manufactured by FDM are fit, load and size.

The design process for items representing these design problems was mapped and steps were categorised with respect to type of action and assigned difficulties corresponding to technical understanding and to technical ability. This permitted the identification of difficult steps in the design process and their relative distribution of occurrence over the design process.

It was also found that it is easier to manipulate than to generate geometry suggesting that the design of useful objects could be carried out by amending imported models from design repositories rather than the generation of new models.

The discussion focussed on the consequences of the study's findings and postulated the requirements and possible functionality of a system that would enable democratisation of design through FDM manufacture. The discussion also considered the, albeit briefly, the need to examine various strategies for achieving democratising including automation, semi-automation, crowd sharing or out-sourcing. These aspects and the knowledge base and supportive requirements are to be examined in future work.

REFERENCES

- KBSI, K. B. S. I. (2016), *A Structured Approach to Enterprise Modeling & Analysis*. Available at: <http://www.idef.com/> (Accessed: 18 December 2016).
- Birtchnell, T. and Hoyle, W. (2014), *3D Printing for Development in the Global South*. Palgrave Macmillan.
- Conner, B. P., Manogharan, G. P. and Meyers, K. L. (2015), 'An assessment of implementation of entry-level 3D printers from the perspective of small businesses', *Rapid Prototyping Journal*, 21(5), pp. 582–597. doi: 10.1108/RPJ-09-2014-0132
- Cross, N., Christiaans, H. and Dorst, K. (1996), *Analysing Design Activity*. John Wiley & Sons.
- Dickens, P. and Minshall, T. (2015), *UK Strategy for additive manufacture - Initial Findings*. Available at: <http://www.amnationalstrategy.uk/wp-content/uploads/2015/05/UK-AM-National-Strategy-Update-Report-2.2.pdf>
- Gebler, M., Schoot Uiterkamp, A. J. M. and Visser, C. (2014), 'A global sustainability perspective on 3D printing technologies', *Energy Policy*. Elsevier, 74(C), pp. 158–167. doi: 10.1016/j.enpol.2014.08.033
- Goudswaard, M., Hicks, B. J., Nassehi, A. and Mathias, D. (2017), 'Realisation of self-replicating production resources through tight coupling of manufacturing technologies'.
- MakerBot (2016), *MakerBot Thingiverse*.
- McCutcheon, R., Pethick, R., Bono, B. and Thut, M. (2014), '3D printing and the new shape of industrial manufacturing', (June), p. 8. Available at: http://www.pwc.com/us/en/industrial-products/assets/3d-printing-next_manufacturing-chart-pack-pwc.pdf
- Noble, D. and Rittel, H. W. (1988), 'Issue-Based Information Systems for Design', *Computing in Design Education [ACADIA Conference Proceedings]*, pp. 275–286. Available at: <http://cumincad.scix.net/cgi-bin/works/Show?ca71>
- Robinson, A. (2014), *The Democratization of Manufacturing and The Roles of Its Citizens*. Available at: <http://cerasis.com/2014/06/02/democratization-of-manufacturing/> (Accessed: 10 December 2016).
- Watkin, H. (2015), *Thingiverse Reaches 1 Million Uploads, 200 Million Downloads*. Available at: <https://all3dp.com/makerbot-thingiverse-reaches-1-million-uploads-200-million-downloads/> (Accessed: 10 December 2016).
- Wittbrodt, B. T., Glover, A. G., Laureto, J., Anzalone, G. C., Oppliger, D., Irwin, J. L. and Pearce, J. M. (2013), 'Life-cycle economic analysis of distributed manufacturing with open-source 3-D printers', *Mechatronics*. Elsevier Ltd, 23(6), pp. 713–726. doi: 10.1016/j.mechatronics.2013.06.002

ACKNOWLEDGEMENTS

The work reported in this paper has been undertaken as part of the Language of Collaborative Manufacturing Project at the University of Bath & University of Bristol, which is funded by the Engineering and Physical Sciences Research Council (EPSRC), grant reference EP/K014196/2. Underlying data are openly available on request to mark.goudswaard@bristol.ac.uk.