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Towards the democratisation of design: A generalised capability model for FDM

Abstract: The manufacture of functional parts via Fused Deposition Modelling (FDM) is inhibited by a lack of understanding of the manufacturing process itself. This results in parts having unpredictable and unreliable mechanical properties. Correspondingly, this paper considers the incorporation of Capability Profiles (CPs) in the design process for FDM as a solution. The evolved requirements of CPs for FDM when compared to traditional subtractive processes are considered and the necessary process information that would be incorporated within them is presented. A review of existing literature of the effect of process parameters on mechanical properties of FDM parts identifies process variability and the effects of shape and scale as areas currently insufficiently studied. To address this, a programme of tensile tests are conducted revealing i) significant variation (26%) in identical test specimens' ultimate tensile strength ; ii) that properties do not scale linearly with specimen size; and iii) that cross-sectional shape directly impacts mechanical performance. The results of these tests are pooled with those from existing literature to define the parameters that need to be included within a capability profile for FDM. The functionality of such a capability profile is shown by demonstrating how these parameters would be used to determine the mechanical properties of an artefact.

Keywords: Democratisation of Design; Filament Deposition Modelling; Mechanical Testing; Material Testing; Capability Profiles

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1 Introduction

The democratisation of design is the process of allowing "more non-designers to become to become involved in idea generation, development and production of products, services or processes" (Fleischmann, 2015). Consequently, it has the potential to facilitate the ultimate agile Product Development Process (PDP) with the end user able to innovate and create products for themselves.

In parallel with the inception and evolution of the concept of democratising design, the paradigm shift to low cost Additive Manufacturing (AM) techniques, such as Filament Deposition Modelling (FDM), has provided a technology platform that can underpin democratisation. FDM offers the potential to de-skill manufacturing without loss of capability (Garrett, 2014) whilst providing significant economic (Wittbrodt *et al.*, 2013) and sustainability benefits (Gebler, Schoot Uiterkamp and Visser, 2014) in the manufacture of day to day consumer goods. In addition to these advantages, FDM (as well as other AM technologies) offer a wide range of design freedoms that permit the realisation of structures not possible by other traditional manufacturing methods (Attaran, 2017).

Permitting people to design and manufacture for themselves is a step towards more agile product development processes. By moving elements of design and manufacturing from the developer to the end user, companies can innovate and develop products more quickly, enabling a faster response to identified customer needs. Through the use of manufacturing process such as FDM, the PDP is simplified and reduced. This is due to manufacture being off-loaded to the end user which results in greatly reduced lead times as physical supply chains are removed by supplying products instantly via digital means.

A corollary of democratising design and manufacture is that non-technical stakeholder groups must either fully or partially fulfil the roles of the traditional design engineer, structural engineer and manufacturing engineer in order to create a functional artefact. A fundamental aim of democratising design therefore is to provide tools than can support non-technical users to carry out tasks normally undertaken by experts. To achieve this, it is necessary provide the user with support in making reasoned design decisions, which, in the design of structural parts would necessitate a Capability Profile (CP) detailing the impact that manufacturing parameters have on the properties of finished parts. Whilst some empirical relationships have been developed for some of these parameters, there is no present method that enables the accurate prediction of part behaviour.

Correspondingly, this paper presents an overall methodology to achieve the democratisation of design with particular attention to the requirements, architecture and population of a capability profile capable of enabling a non-technical user to design and manufacture parts with reliable properties. It represents a new design approach that enables product customisation and improvements in process flexibility.

Whilst the presented methodology can be applied to other AM techniques, this paper focuses on its application to the FDM process. This is because of the previously mentioned sustainability and economic benefits that it affords, and also that it is the most widely used AM technique, accounting for 69% of printers used in the consumer market (Holst, 2018).

The novelty in the work presented in this paper is twofold. Firstly, experimental testing explores the effect of shape and scale on the mechanical behaviour of FDM parts – two properties not considered in existing work. Secondly, the development and use of an FDM capability profile is novel, and its incorporation within the design for FDM process enables appraisal of the feasibility of such an approach in creating parts with reliable properties.

This paper begins with an overview of existing applications of capability profiles in traditional manufacturing processes. The FDM process is then presented and, based upon this, the incorporation of capability profiles in the AM design process is proposed. A comprehensive literature review is carried out to elucidate the impact of manufacturing parameters on the mechanical properties of parts manufactured by FDM. Knowledge gaps identified from this review are used to frame experimental testing which is undertaken to find the FDM process variability and effects of shape and scale on the mechanical behaviour of parts. Finally, this is drawn together to identify the key parameters required in a capability profile and a manner in which they can be incorporated is proposed. An overview of the paper methodology is shown in Figure 1.

FIGURE 1 - METHODOLOGY DIAGRAM SHOWING WORKFLOW THROUGH PAPER

2 Existing Capability Profiles

A capability profile is a time-sensitive image of a manufacturing resource, representing the capabilities that a specific machine tool will be able to provide at a specific time on a specific product (Newman and Nassehi, 2009). They relate the effect that machining parameters have on part properties by accounting for changes to the manufacturing resource over time. When this is coupled with information about the stock material and a part's geometry the characteristics of a workpiece can be described. This can take place at four levels ranging from geometry of the element to the chemical integration at the atomic scale (Klocke, Brinksmeier and Weinert, 2005):

- Macro (accuracy in shape and dimension).
- Micro (surface topography).
- Meso (material structure and properties).
- Nano (tribo-chemical reaction layers).

Capability profiles can be incorporated in a number of ways within existing CAx chains to support the manufacturing process. The most common CAx chain used in manufacturing today involves the generation of a part in Computer Aided Design (CAD) software. This is then transferred to a Computer Aided Process Planning (CAPP) or Computer Aided Manufacturing (CAM) system where process information is added to the geometry. This information typically includes tool definitions, feeds, speeds and machining strategies. A post-processor is used to move the information from a product space in CAM to the machine space in the CNC (Newman and Nassehi, 2007). Within this process, CPs are typically used in process planning which consists of the consolidation of activities that seek to define the steps required to alter the shape of raw stock material into the desired product (ElMaraghy, 1993). The use of CPs allows the selection of appropriate manufacturing resources for a given part.

Figure 2 shows the process planning process incorporating manufacturing capability profiles. The manufacturing production resource is profiled by combining sensed data from the resource itself, nominal resource information and production policies. These allow tool wear to be measured and compared against an allowable threshold that would yield the manufacture of an acceptable part.

FIGURE 2 - IDEF-0 REPRESENTATION OF PROCESS PLANNING FOR SUBTRACTIVE PROCESS WITH MANUFACTURING CAPABILITY PROFILES. FROM (Newman and Nassehi, 2009) **(REPRODUCED WITH PERMISSION)**

For traditional subtractive methods the development of a number of capability profiles can be found in existing literature including a capability profile for hard cutting and grinding (Klocke, Brinksmeier and Weinert, 2005) and a review machining parameters in the turning process that effect finish part properties (Bartarya and Choudhury, 2012). Additionally the integrated use of manufacturing resource profiles is proposed in CAPP in order to optimise the generation of process plans (Newman and Nassehi, 2009). CPs are also used to provide a tool health data model (Vichare *et al.*, 2015).

3 Capability Profiles for FDM

Capability profiles for traditional manufacturing methods are based upon mechanical properties of materials and the effect that various manufacturing processes have on these.

FIGURE 3 – KEY FDM PRINTING PARAMETERS

Emerging manufacturing technologies such as FDM offer far greater flexibility in manufacturing outcome than traditional subtractive processes. This enables the production of structures that would be impossible by traditional (mostly subtractive) manufacturing methods (Garrett, 2014) and also permits the internal structural optimisation of FDM parts for strength (Gopsill and Hicks, 2016), mass distribution (Prévost *et al.*, 2013) and moment of inertia (Bächer *et al.*, 2014). This flexibility is enabled by the additive, layer-wise deposition of material and the large number of manufacturing parameters that can be independently controlled in the generation of FDM tool paths. A number of key manufacturing parameters are demonstrated in Figure 3 and include build orientation, layer height, print speed, travel speed, extruder temperature, air gap, raster thickness, raster angle, number of solid shells, bed temperature and infill percentage. Whilst by no means an exhaustive list, they give an idea of the size and complexity of the solution space afforded by FDM, as well as an indication of the number of parameters that would need to be included in an FDM capability profile.

FIGURE 4 - IDEF-0 REPRESENTATION OF PROPOSED INCORPORATION OF CAPABILITY PROFILE IN DESIGN AND MANUFACTURING PROCESS FOR FDM.

The manufacturing parameters therefore not only shape the manner in which the physical product is to be made, but also the very nature of the design itself. With respect to existing CAx chains, incorporation of manufacturing capability must be considered during the design process, not only in the CAPP or CAM stages. This is due to a drive towards 'built as designed' where products are expected to function and behave exactly as predicted (Pətrəucean *et al.*, 2015) and also a more widespread uptake of generative design approaches such as that provided by Autodesk (Autodesk Inc, 2018). These generative approaches enable the generation of parts based upon functional requirements and manufacturing capability. As a result, a manufacturing resource capability profile shapes and directs the design of the part and therefore needs to be included earlier in the design and manufacturing process than with traditional CPs.

Figure 4 presents an IDEF-0 representation of how a capability profile for FDM would be determined and incorporated within a generative design process that concomitantly generates both manufacturing and structural parameters that permit a part to meet its functional requirements. Whilst it is not within the scope of this paper to explore the manner in which this could be achieved, an overview of such a process is presented in literature (Goudswaard, Hicks and Nassehi, 2018).

The process planning for subtractive processes (Figure 2) uses the manufacturing resource capability as a control for the process planning stage to transform product information (such as a static CAD model) into a capability adjusted process plan. In the proposed process for FDM (Figure 4) however, it uses it as control to generate structural and manufacturing parameters based upon the object requirements. Manufacturing capability therefore has a direct influence on the design of a product, not just in the way it's manufactured, as it is necessary to exploit the flexibility of the process.

As shown in the IDEF representation (Figure 4), the mechanism for developing a capability profile for FDM would be via geometric and mechanical testing of parts. This is due to uncertainty surrounding parts manufactured via FDM which will be explored in greater detail in Section 4. Whilst sensing (such as for subtractive processes shown in Figure 2) might be appropriate in the future once the FDM process is better understood, for now physical testing of parts is the only way of developing a thorough understanding of a manufacturing resource's capability.

Having explored CPs for extant processes and proposed how they would be incorporated within the FDM process. The following section explores information about the manufacturing process that would need to be incorporated within CP. In doing this, research gaps are identified which in turn direct testing that needs to be carried out to deduce this information.

4 Existing FDM process knowledge

Having identified the differing requirements of capability profiles for FDM compared to subtractive processes and alluded to the breadth of parameters that might need to be included in a CP for FDM, this section explores existing process knowledge for FDM. It allows the identification of extant empirical relationships between manufacturing parameters and mechanical properties which can be incorporated within a capability profile for FDM. It also permits gaps in existing research to highlighted in order to direct the undertaking of further experimental testing.

Early applications of FDM as a manufacturing technology were largely aesthetic or for prototyping, with a focus on high quality prints to generate consistent, geometrically accurate parts with good surface finishes but with little consideration of their functional performance. Consequently, various methods of geometric benchmarking have been proposed to assess these elements of an FDM printer's capability (Rebaioli and Fassi, 2017).

As the technology has developed further and FDM has become more capable of producing structural parts, studies have sought to evaluate and characterise the relationship between mechanical properties and manufacturing parameters. From these studies a number of empirical relationships have been deduced:

1) Studies of layer height have generally found that larger layers increase part strength (Tymrak, Kreiger and Pearce, 2014) (Onwubolu and Rayegani, 2014) (Alafaghani *et al.*, 2017) (Croccolo, De Agostinis and Olmi, 2013) (Sood, Ohdar and Mahapatra, 2010) (Lanzotti *et al.*, 2015).

2) Studies of part build orientation have revealed that parts are found to be weakest in the direction of build (Tymrak, Kreiger and Pearce, 2014) (Onwubolu and Rayegani, 2014) (Alafaghani *et al.*, 2017) (Croccolo, De Agostinis and Olmi, 2013) (Sood, Ohdar and Mahapatra, 2010) (Lanzotti *et al.*, 2015).

3) Parts are strongest with raster angle in direction of the applied load and increased raster width increases part strength (Onwubolu and Rayegani, 2014) (Croccolo, De Agostinis and Olmi, 2013) (Casavola *et al.*, 2016) (Sood, Ohdar and Mahapatra, 2010) (Lanzotti *et al.*, 2015).

4) A negative air gap is found to increase part strength (Onwubolu and Rayegani, 2014) (Croccolo, De Agostinis and Olmi, 2013) (Sood, Ohdar and Mahapatra, 2010).

5) An increased infill percentage is found to increase part strength (Alafaghani *et al.*, 2017).

6) An increase in the number of solid shells increases part strength (Croccolo, De Agostinis and Olmi, 2013) (Lanzotti *et al.*, 2015).

7) Extrusion temperature is shown to greatly affect the mechanical properties of the printed parts with distinct optimum extrusion temperature ranges existing for different materials (Alafaghani *et al.*, 2017) (Wittbrodt and Pearce, 2015).

8) Mechanical properties are found to vary significantly with material type, build (Tymrak, Kreiger and Pearce, 2014) (Onwubolu and Rayegani, 2014) and colour (Wittbrodt and Pearce, 2015).

From the review of existing literature, a number of research gaps requiring addressing can be identified.

While the reported studies have established a number of empirical relationships, many used relatively small sample sizes (of 3 (Onwubolu and Rayegani, 2014) (Alafaghani *et al.*, 2017) (Sood, Ohdar and Mahapatra, 2010) (Lanzotti *et al.*, 2015) or 5 (Croccolo, De Agostinis and Olmi, 2013) (Casavola *et al.*, 2016)) with little reporting of the process variability, or identified very high variability in mechanical properties (Lanzotti *et al.*, 2015) compared to the raw material (Casavola *et al.*, 2016). As a consequence of this, while the empirical relatives are directed, no magnitudes have been established with any confidence. A research gap is therefore identified as the identification of the variation in Ultimate Tensile Strength (UTS) for test pieces manufactured with identical material and process settings for a much larger sample size than those in previous studies. The need to clarify variability of the FDM process is specifically identified in a comprehensive review paper on the mechanical properties of parts manufactured via FDM (Popescu *et al.*, 2018).

Additionally, existing studies have largely tested according to ASTM standards for material testing (Tensile (ASTM International, 2003), Compressive (ASTM, 2016) & Flexural (ASTM-D790-17, 2017)) and test the properties of the prescribed specimen which is assumed to be indicative of properties of other shapes and sizes made of the same material. This assumption is currently un-substantiated by experimental evidence, and due to the layer wise construction of the manufacturing process might not be valid. An additional research gap is therefore identified as eliciting the effect of shape and scale on the mechanical properties of parts.

Whilst a large number of empirical relationships between manufacturing parameters and mechanical properties, a variety of printers, polymers, slicing software and process parameters were used, meaning that the generalisation of existing results is very difficult (Popescu *et al.*, 2018). It is therefore necessary to undertake a comprehensive testing regime on a single printer and material in order to determine conclusively the effect that all print parameters have on mechanical properties.

In light of these identified research gaps, the following sections detail experimental testing undertaken to determine the variation in UTS of tensile test specimens and also the effects of shape and scale on the mechanical properties of parts.

5 Variance Determination

To determine the variance in mechanical properties of parts manufactured by FDM, tensile tests were undertaken with batch sizes larger than those found in existing literature.

Test specimens were manufactured on an Ultimaker 2 using Ultimaker branded silver metallic Polylactic Acid (PLA) filament. Tensile tests were undertaken on an Instron 3343 tensile test machine with loads measured with a 1 kN Instron force transducer. Specimens were extended at a rate of 1mm/min until break. Figure 6a shows the batch manufacture of specimens, and Figure 6b the experimental test set-up.

Figure 5 - Dimensions of test specimen for variance tensile tests. Dimensions prefixed by W or T signify a measured width or thickness for each specimen. Gauge length is not shown as specimen extension was not measured.

Tests for variance determination used an altered ASTM:D638 (ASTM International, 2003) specimen (Shown in Figure 5). A larger radius was added to reduce the likelihood of failure occurring outside of the reduced area (as also done by Croccolo et al (Croccolo, De Agostinis and Olmi, 2013)). Specimen dimensions are shown in Figure 5. Eight batches of five samples were manufactured at infill values of 20% and 100%. These two values represent the extremes with an infill below 20% resulting in an inconsistent top layer (compromising the overall shell) and 100% infill resulting in a solid part which negates the effect of infill pattern. Other print parameters of layer height, wall thickness, top/bottom thickness, infill pattern, extruder temperature, print speed, travel speed, print cooling and print sequence were all kept constant across the batches.

Figure 6 - (a) Picture of specimen manufacture (b) Tensile test set-up

5.1 Results

Table 1 is an extract of the collective specimen measurements and the results taken during the tensile tests. Samples are considered collectively, and within the batches in which they were manufactured. Whilst all samples were printed with the same filament, different rolls were used for some of the samples. To account for any change in properties caused by this, additional samples were tested. For this reason, more sets of 100% infill specimens were tested than 20% infill – 5 & 3 respectively.

TABLE 1 – RESULTS OF TENSILE TESTS FOR VARIANCE DETERMINATION. STANDARD DEVIATION IS ABBREVIATED TO SD, PERCENTAGE RANGE IS DEFINED AS THE RANGE DIVIDED BY THE MEAN EXPRESSED AS A PERCENTAGE

5.2 Discussion

The different samples demonstrated tensile strengths ranging by 24% to 26% percent when considered collectively and 4% to 17% intra-batch. This section explores the impact of extruder temperature fluctuations, whether the variability can be correlated to other part properties, and lastly how knowledge (characterisation) of this variability can be used when designing parts for manufacture via FDM.

5.2.1 Thermal imagine of FDM process

An exploratory study was carried out to investigate fluctuations in extruder temperature as a possible cause of the variation in tensile strengths for the identical samples. This was investigated as Alafaghani et al. found that changing the extrusion temperature set point resulted in significant alterations in tensile strength (Alafaghani *et al.*, 2017) (shown in Table 2). It has also previously been identified that filament temperature is a critical parameter in dictating part strength (Sun *et al.*, 2008). This study sought to identify how the extruder temperature fluctuates around the set point during the duration of a print.

TABLE 2 UTS VS. EXTRUSION TEMPERATURE (FROM (Alafaghani *et al.*, 2017))

This effect was explored by analysing the change in extruder temperature during the print using a FLIR T650sc thermal imaging camera. A test piece of a single raster width was manufactured under the same conditions as those in the manufacture of the tensile test specimens and was filmed at 30 frames per second. The video was then analysed using FLIR IR Tools+ software. Average, maximum and minimum temperatures were extracted from four regions: deposited filament (Bx2); high in the nozzle (Bx3); mid nozzle (Bx4) and nozzle exit (Bx5). These regions are shown in Figure 7.

FIGURE 7 - IR IMAGE OF EXTRUDER DURING PRINT SHOWING AREAS IN WHICH TEMPERATURES WERE MEASURED

Table 3 shows the measured results for temperature fluctuations in these areas. Over the course of a print the high and mid nozzle areas show roughly 2°C changes whilst the deposited filament and nozzle exit areas show fluctuations of almost 5°C. When coupled with the temperature effects shown in Table 2, a 5°C temperature fluctuation could give rise to a 14-30% change in UTS. Therefore, correlation is observed between extruder temperature fluctuations and UTS, suggesting temperature fluctuations could be a cause of the variation in mechanical properties.

TABLE 3 - MEASURED TEMPERATURE FLUCTUATIONS DURING PRINT

FIGURE 8 - SCATTER PLOT SHOWING STOCHASTIC RELATIONSHIP BETWEEN UTS AND OTHER PART PROPERTIES

5.2.2 Relationships between part properties and load

Given the large range of experimentally determined tensile strengths, analysis was carried out to elicit whether there existed any relationship between other part properties and tensile strength. The other part properties explored were cross sectional area at break, part mass and the cross section at break divided by the mass. These were selected as their measurements were found to vary significantly in the test specimens and are properties that can be measured non-destructively. This is important because if a relationship were to be found it would allow the correlation and hence prediction of a part property that could otherwise only be determined through destructive testing.

Scatter plots showing their respective relationships against UTS for the 100% infill samples are given in Figure 8. All the relationships can be observed to be stochastic signifying that the UTS cannot be reliably correlated with the considered part properties (cross-sectional area and mass). A similar relationship was observed for the samples with 20% infill.

5.2.3 Applying the findings to design tasks

Given the high variability in tensile strengths and that these cannot be correlated to other part properties, a statistical model can be developed to predict the likelihood of a designed part meeting a defined strength requirement. This section highlights how such a model was developed based upon the results of the 100% infill test samples.

A Shapiro-Wilk test for normality (Shapiro and Wilk, 1965) was carried out on the break loads and UTSs of all the 100% infill samples. When considered both individually and collectively the sample sets were found to be normally distributed with means and standard deviations as defined in Table 1. Probability density functions can then be generated for the 100% infill samples. These are shown in Figure 9 for sample UTS. These can be used to predict the likelihood a design will meet a given requirement. It can be noted that one of the curves (Sample 1) is significantly further to the left than the others. We believe that it is attributed to a change in filament roll during the manufacture of the specimens.

With respect to the formation of a CP for FDM, a statistical model, such as the one proposed, can be used within a capability profile to provide a confidence level that a part manufactured will have the required mechanical properties.

Figure 9 – Probability Density Functions for UTS of 100% infill specimens

5.2.4 Concluding remarks

The section has presented experimental testing results that permit the elucidation of the variability of FDM process. Results suggest that this is caused by extruder temperature fluctuations during manufacture.

The presented statistical models enable the prediction of part properties. These can be directly used within a CP for FDM as they allow the prediction of variety of outcome that can be expected in the manufacture of a part.

6 Shape & scale effect determination

As stated in section 4, it is currently unclear whether the mechanical properties of FDM parts are consistent with respect to shape and scale. The aim of these tests was therefore to elicit the significance of shape and scale on the mechanical properties of parts, in order to understand if they need to be included in a CP for FDM. To determine the effect of shape tensile tests were carried out on samples with different cross sections but constant area. To determine the effect of scale, tests were carried out on samples with the same cross section but different areas.

Tensile tests were undertaken on an Instron 3343 tensile test machine with loads measured with a 1 kN Instron force transducer. Specimens were extended at a rate of 1mm/min until break.

Six batches of six specimens were manufactured on an Ultimaker 2 with Ultimaker branded silver PLA. All samples were printed with the same reel of filament.

An amended test specimen was used for these tests compared to that which was used to deduce the effect of variance. This was to enable a significant variance in cross-sectional shape and area, whilst simultaneously permitting variance of the solid shells printing parameter which can only be varied in discrete increments of nozzle size (0.4mm for the tests carried out). The cross sections manufactured are shown in Figure 10.

The first set of specimens concerned with shape all used identical printing parameters, a constant cross sectional areal with rectangular, circular and triangular cross sections respectively (shown in Figure 10).

FIGURE 10 - SAMPLE CROSS SECTIONS FOR DETERMINING EFFECT OF SHAPE

The second set of specimens used a rectangular cross section of varying area but constant aspect ratio. Identical manufacturing parameters were used with the exception of the ½ scaled rectangular cross section which also scaled the solid shells parameter in line with the cross section. These cross-sections are shown in Figure 11.

The reduced area section was reduced in length when compared with ASTM specimen in order to ensure break occurred within the length of the extensometer (50mm). A plan of the test specimen is shown in Figure 12.

FIGURE 11 - CROSS SECTIONS OF TESTED SAMPLES FOR DETERMINING EFFECT OF SCALE

FIGURE 12 - DIMENSIONS OF TEST SPECIMEN FOR SHAPE & SCALE TESTING

6.1 Results

Results of the tests carried out to deduce the effects of shape and scale are shown in Table 4. A moderate variation (9% with respect to UTS) can be observed due to the effect of cross section shape, and a much more significant variation (38% with respect to UTS) can be observed due to the effect of scale. It is noteworthy that maximum break load does not scale linearly with the size of the part.

TABLE 4 - RESULTS OF TENSILE TESTING TO EXPLORE THE EFFECTS OF SHAPE AND SCALE. STANDARD DEVIATION IS ABBREVIATED TO SD, PERCENTAGE RANGE IS DEFINED AS THE RANGE DIVIDED BY THE MEAN EXPRESSED AS A PERCENTAGE. BASELINE REFERS TO SAMPLE 4.

6.2 Discussion

Having identified non-linearity in mechanical performance caused by scale and variance due to cross-sectional shape it is important to identify a possible cause for the variation.

The ratio of solid shells to infill can be observed to have a significant impact on a specimen’s tensile properties. This can be attributed to the observed non-linearity of the ratio as the specimens are scaled. It is suggested in existing literature that solid shells contribute more to part strength than infill (Goudswaard, Hicks and Nassehi, 2018). Two identical cross-sections with different ratios of infill to solid shell would therefore exhibit different mechanical performance. This is demonstrated in the presented testing results. Table 5 demonstrates how the ratio of shell to infill changes as rectangular test specimens are scaled. When maintaining a constant top/bottom layer and solid shells thickness the ratio can be observed to vary from 1.08:1 to 2.21:1.

TABLE 5 - EFFECT OF SCALE ON RATIO OF INFILL TO SOLID SHELL

Whilst the ratio of infill to solid shell is found to have a significant effect when parts are scaled, when explored as a cause for the observed variation in mechanical performance due to change in cross sectional shape, the ratio of shell to infill cannot be directly identified as a cause. Although the geometric changes do alter the ratio of solid shell to infill (as can be seen in Table 6), no clear relationship can be observed. A number of other factors could contribute to the differing mechanical performance, including part cooling and stress concentrations accelerating failure of the specimens.

TABLE 6 - EFFECT OF SHAPE ON RATIO ON INFILL TO SOLID SHELL

6.2.1 Concluding remarks

Cross sectional shape does have an effect on the mechanical performance of the components and is shown to causes variation in UTS of 3% to 9%. A precise cause for this is not identified. The effect of scale is significant, and mechanical properties are shown to have a non-linear relationship with cross-sectional area. This is attributed to the differing ratios of solid shell to infill as the parts are scaled.

7 Developing an FDM capability profile

The paper so far has posited a manner in which capability profiles can be incorporated into the design for FDM process, reviewed existing knowledge surrounding the manufacturing process itself and presented results from experimental testing to expand this extant knowledge. This section explores what process knowledge is necessary for a capability profile and how this can be drawn together to enable the prediction of a part's mechanical behaviour based upon an input geometry and manufacturing parameters. The parameters included are those identified from literature as having a significant impact on properties of finished parts and also those that need to be defined by the user in the slicing processes. These parameters can thus be divided into three groups according to the nature of the impact they have on the manufactured part:

- Group 1 consists of those that directly affect a part's behaviour by altering the mechanical properties (such as UTS or Young's Modulus)
- Group 2 consists of parameters that affect the post-slice geometry and thus alter the shape properties of parts.
- Group 3 includes those parameters that affect both of the above (layer height for example alters the UTS but also influences the way geometry is sliced).

Essential manufacturing parameters for a capability profile are shown in Table 7. These are assigned one of the three parameter groups defined above and also a description as to how mechanical behaviour is influenced by the parameter. Indicative trends from literature are also included.

TABLE 7 - HOW MANUFACTURING PARAMETERS ARE INCORPORATED INTO AN FDM CAPABILITY PROFILE. ROW COLOURS CORRESPOND TO PARAMETER GROUP

Figure 13 shows an IDEF0 diagram of how the defined groups of manufacturing parameters are used to elicit a part's mechanical behaviour. Specific material properties are calculated by adjusting a normative set of properties with the effects caused by manufacturing parameter groups 1 & 3 and are defined for both infill and solid shells respectively. Part geometry is sliced incorporating manufacturing parameter groups 2 & 3. The sliced geometry provides area moments and quantities of material for both infill and solid shells. When combined with the specific material properties these enable the prediction of a part's mechanical behaviour.

FIGURE 13 - IDEF0 DIAGRAM OF HOW CAPABILITY PROFILE USES MANUFACTURING PARAMETERS TO CALCULATE MECHANICAL BEHAVIOUR

8 Discussion & Further Work

The use of capability profiles in the design process for FDM can enable the democratisation of design by involving non-technical stakeholders in the design process, whilst leveraging the large design space afforded by FDM and other AM technologies. Two important questions to consider with respect to the implementation of CPs for FDM is how would they be generated and by who?

Because of the size of the FDM design space and the large, ever-increasing variety of printers and materials available, the creation of capability profiles would need to be undertaken in two phases. General capability profiles would need to be created by printer manufacturers (experts) for particular types of printers, these would then be refined collaboratively by the crowd (non-experts) to account for printer-specific variation manufacturing capability. This approach to CP generation leverages the affordances of both experts and the crowd respectively.

Generalised capability profiles would be created by printer manufacturers and would involve mechanical testing of the parameters that have been identified in this paper. These would be carried out by 'expert' design, structural and manufacturing engineers. The relationships between parameters would be established and these would form the basis for a model that would be able to predict a part's mechanical behaviour. These relationships would however require refinement in order to enable the fabrication of repeatable and reliable parts on a specific printer.

This refinement could be carried out via means of a simple structural benchmarking artefact that could be manufactured and tested for mechanical performance. This would be similar to existing geometric benchmarking artefacts, such as Benchy (http://www.3dbenchy.com/), that are used to assess a 3D printer's geometric capability. The manufacture and test of a structural test piece would permit comparison of the performance of an actual printed part to that predicted by the general CP. The results of these tests are then incorporated as correction factors within the general CP, allowing it to be individualised. Thus, providing a user with an accurate CP specific to their printer. Interpreting and incorporating the results from testing these artefacts would be carried out by 'non-experts' from the crowd. Existing crowd-sourcing platforms such as Mechanical Turk (Amazon, 2017) or design repositories such as Thingiverse (MakerBot, 2019) could provide suitable environments for generating and sharing necessary information.

Through review of existing literature and the experimental work undertaken in this paper, there is a need to review the testing procedures used to determine the mechanical characteristics of FDM parts. Existing testing strategies are based upon the determination of mechanical properties. But given that these properties are not consistent for shape or size, amended test procedures are necessary to permit better elucidation of the effect of manufacturing parameters on mechanical properties. The design of an appropriate functional test piece would allow the assessment of the effect of manufacturing parameters, rather than the current methods which are used to determine the mechanical properties of the material rather than the specimen.

With respect to continuing further work, in this paper existing empirical studies from literature have been drawn together and complemented with further experimental testing in order to work towards a comprehensive capability profile for FDM. As has already been stated, much work already carried out has used a wide variety of polymers, printers, slicing software and process parameters making it difficult to generalise the findings (Popescu *et al.*, 2018). Further work to be undertaken therefore will look to undertake an extensive testing regime on a single printer. This will allow for greater understanding of the FDM process by deducing the interdependencies of the manufacturing parameters and the manner in which they affect properties of manufactured parts.

The tests undertaken and presented within this paper only consider their tensile properties. It is therefore necessary to undertake further testing to ascertain whether the findings in this paper remain true for other mechanical properties such as flexion and compression.

9 Conclusion

This paper has proposed the incorporation of capability profiles into the design process for FDM as a means of facilitating agile project development. Information surrounding the gaps in existing knowledge of the FDM process have been identified. Subsequent experimental work is undertaken to determine the variability in the process and also the effects of shape and scale on the tensile properties of specimens. The results of these demonstrated variability in tensile strength of up to 26% in identical specimens. Non-linearity is observed with respect to tensile strength as the parts are scaled with variation of up to 38%. Changing ratios of infill to solid shell are identified as a cause for this. Variations in mechanical performance of up to 9% are also observed by changes in cross sectional shape. The findings of these tests were brought together to define the parameters that would need to be considered within an FDM capability profile as: layer height, build orientation, raster angle, raster width, infill pattern, infill percentage, top/bottom layers, solid shells, extrusion temperature, material type, variability & geometry. A manner in which these could be incorporated is also proposed with the parameters grouped according to whether they directly impact mechanical properties such as UTS, the sliced geometry, or both.

10 Acknowledgements

The work reported in this paper has been undertaken as part of the ProtoTwin project (Improving the product development process through integrated revision control and twinning of digital-physical models during prototyping). The work was conducted at the University of Bristol in the Design and Manufacturing Futures Lab (http://www.dmf-lab.co.uk) and is funded by the Engineering and Physical Sciences Research Council (EPSRC), Grant reference EP/R032696/1.

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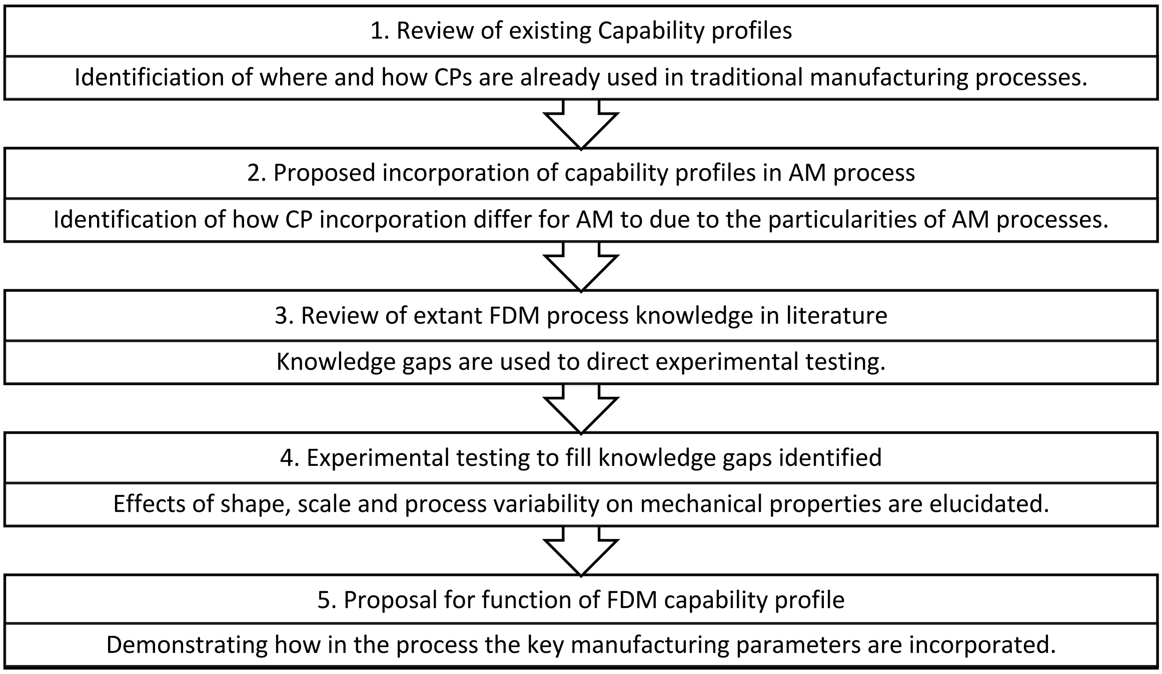
12 Tables and Figures



1. Review of existing Capability profiles

Identificiation of where and how CPs are already used in traditional manufacturing processes.

2. Proposed incorporation of capability profiles in AM process

Identification of how CP incorporation differ for AM to due to the particularities of AM processes.

3. Review of extant FDM process knowledge in literature

Knowledge gaps are used to direct experimental testing.

4. Experimental testing to fill knowledge gaps identified

Effects of shape, scale and process variability on mechanical properties are elucidated.

5. Proposal for function of FDM capability profile

Demonstrating how in the process the key manufacturing parameters are incorporated.

FIGURE 1 - METHODOLOGY DIAGRAM SHOWING WORKFLOW THROUGH PAPER

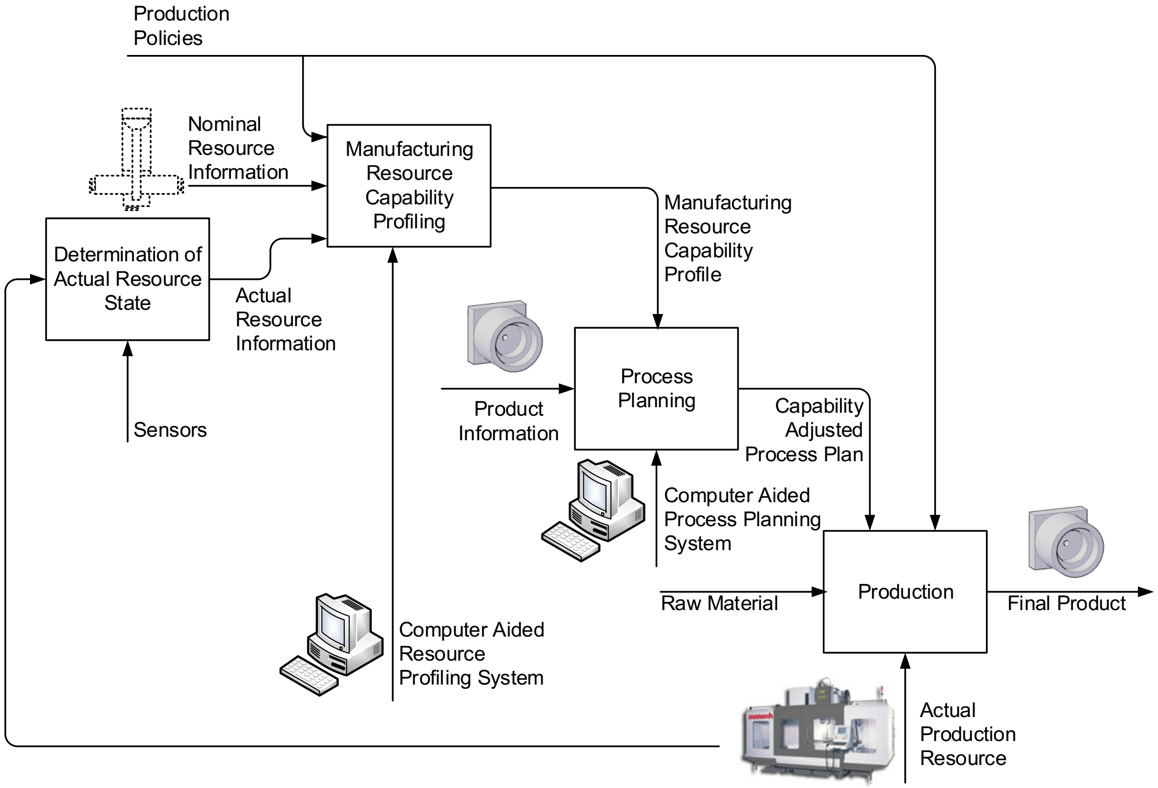


FIGURE 2 - IDEF-0 REPRESENTATION OF PROCESS PLANNING FOR SUBTRACTIVE PROCESS WITH MANUFACTURING CAPABILITY PROFILES. FROM (Newman and Nassehi, 2009) (REPRODUCED WITH PERMISSION)

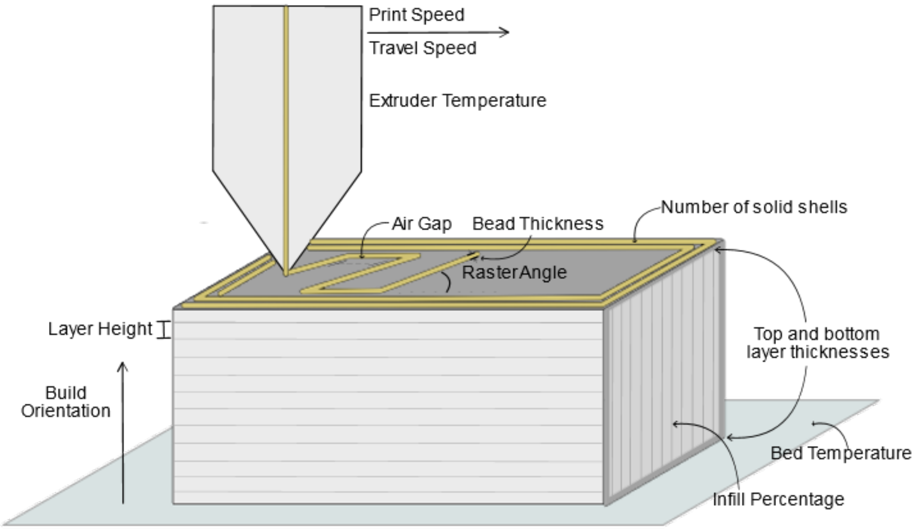


FIGURE 3 – KEY FDM PRINTING PARAMETERS

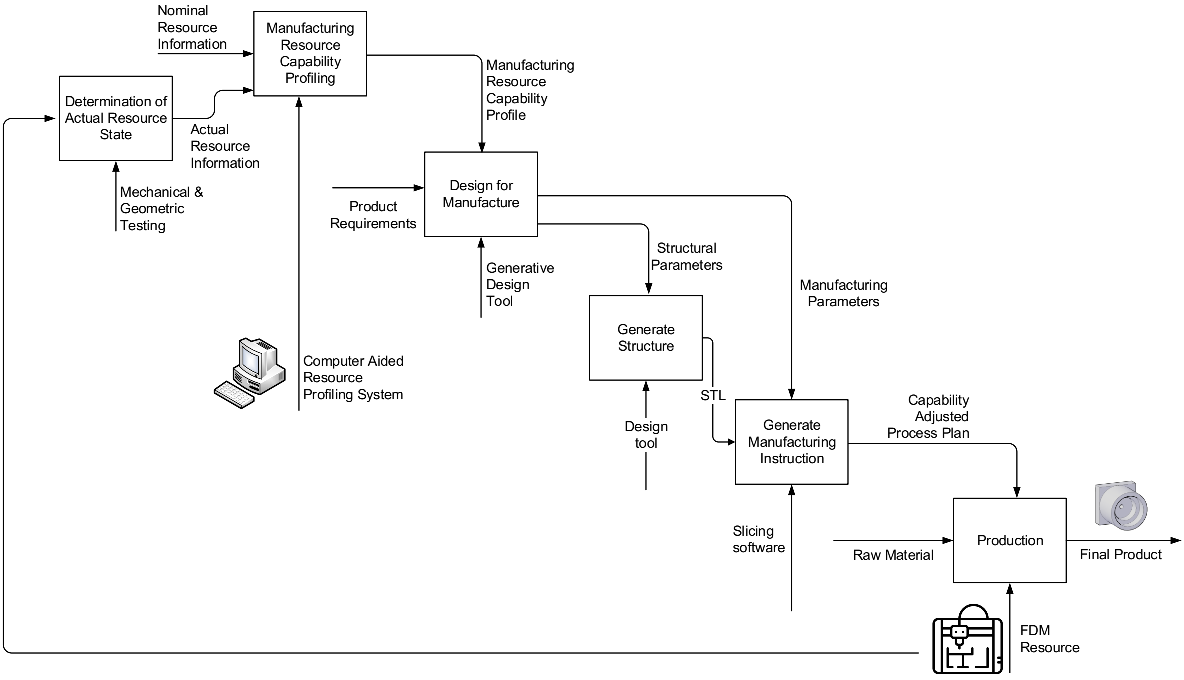


FIGURE 4 - IDEF-0 REPRESENTATION OF PROPOSED INCORPORATION OF CAPABILITY PROFILE IN DESIGN AND MANUFACTURING PROCESS FOR FDM.

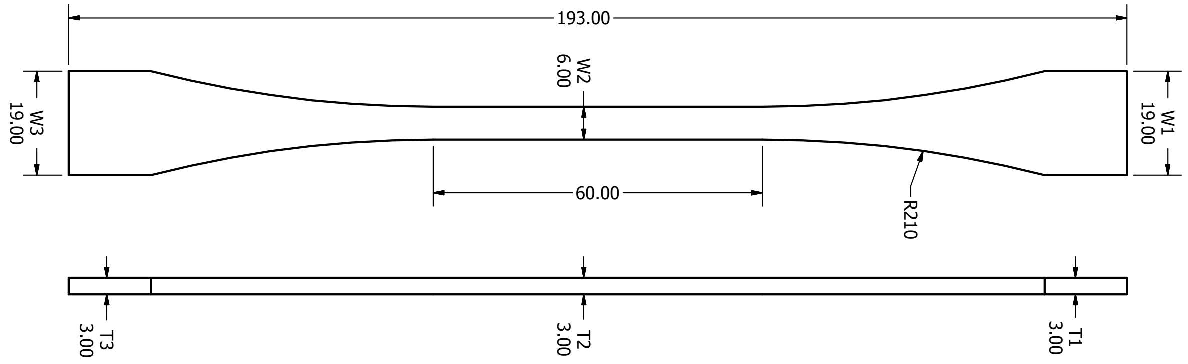
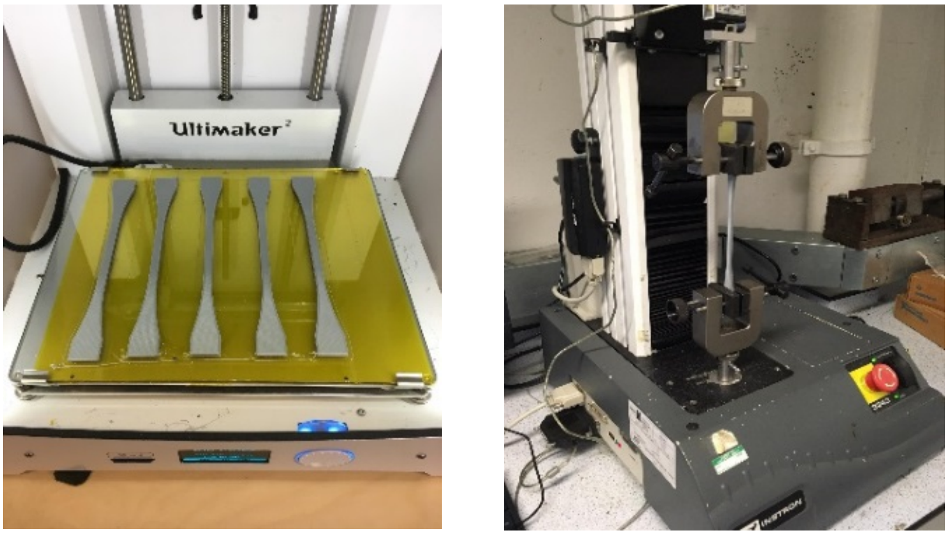


FIGURE 5 - DIMENSIONS OF TEST SPECIMEN FOR VARIANCE TENSILE TESTS. DIMENSIONS PREFIXED BY W OR T SIGNIFY A MEASURED WIDTH OR THICKNESS FOR EACH SPECIMEN. GAUGE LENGTH IS NOT SHOWN AS SPECIMEN EXTENSION WAS NOT MEASURED.



(a) (b)

FIGURE 6 - (A) PICTURE OF SPECIMEN MANUFACTURE (B) TENSILE TEST SET-UP

TABLE 1 – RESULTS OF TENSILE TESTS FOR VARIANCE DETERMINATION. STANDARD DEVIATION IS ABBREVIATED TO SD, PERCENTAGE RANGE IS DEFINED AS THE RANGE DIVIDED BY THE MEAN EXPRESSED AS A PERCENTAGE

SAMPLE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**20% total**	**100% total**
Infill %	20	20	20	100	100	100	100	100	20	100%
Sample size	5	5	5	5	5	5	5	5	15	25
Break Load (N)	539	567	592	686	766	766	755	749	566	745
SD (N)	16.5	23.8	26.8	29.8	38.1	27.1	35.1	34.8	30.7	44.5
% range	7	11	11	13	13	9	14	14	21	24
Max (N)	557	598	639	737	822	801	803	812	639	822
Min (N)	519	535	575	646	719	735	700	707	519.3	646.3
Range (N)	37.4	63.5	64.0	90.7	102	66.3	102	106	120	176
UTS (Mpa)	29.9	32.4	33.9	38.0	43.4	43.7	43.5	43.2	32.0	42.4
SD (MPa)	0.4	1.4	1.9	1.1	1.9	1.3	2.4	2.4	2.12	2.94
% range	4	12	14	8	12	7	17	17	24	26
Max (N)	30.5	34.5	37.0	39.4	46.1	45.3	46.5	47.3	37.0	47.3
Min (N)	29.4	30.7	32.3	36.2	41.0	42.1	39.2	39.9	29.4	36.2
Range (N)	1.1	3.8	4.7	3.2	5.1	3.2	7.3	7.4	7.6	11.1
W2 (mm)	6.02	6.03	6.01	6.04	6.03	6.03	5.98	5.95	6.02	6.01
SD (mm)	.019	.013	.023	.016	.018	.015	.040	.022	.018	.045
% Range	.66	.5	1	.66	.83	.7	1.7	1	1.0	2.3
Max (mm)	6.04	6.04	6.05	6.05	6.06	6.05	6.04	5.98	6.1	6.1
Min (mm)	6	6.01	5.99	6.01	6.01	6.01	5.94	5.92	6.0	5.9
T2 (mm)	3.00	2.90	2.90	2.99	2.92	2.91	2.91	2.92	2.93	2.93
SD (mm)	.067	.036	.048	.059	.027	.022	.063	.041	.066	.055
% Range	5.0	2.8	3.8	5.4	2.4	2.1	5.8	3.8	8	9
Max (mm)	3.09	2.96	2.97	3.09	2.95	2.94	3.01	2.99	3.1	3.1
Min (mm)	2.94	2.88	2.86	2.93	2.88	2.88	2.84	2.88	2.9	2.8
Mass (g)	5.05	4.93	4.98	6.79	6.77	6.76	6.78	6.83	4.98	6.78
SD (g)	0.12	0.08	0.07	0.15	0.09	0.08	0.02	0.02	0.100	0.083
% Range	5	4	4	5	3	3	1	1	8	5
Max (g)	5.19	5.03	5.09	6.96	6.89	6.88	6.80	6.86	5.2	7.0
Min (g)	4.92	4.81	4.89	6.62	6.66	6.65	6.75	6.81	4.8	6.6

Table 2 UTS vs. extrusion temperature (from (ALAFAGHANI ET AL., 2017))

Extrusion Temperature (^{o}C)	**UTS (MPa)**	**% change from 180^{o}C**
175	28.59	-30%
180	40.58	0%
185	46.06	14%
205	43.79	8%

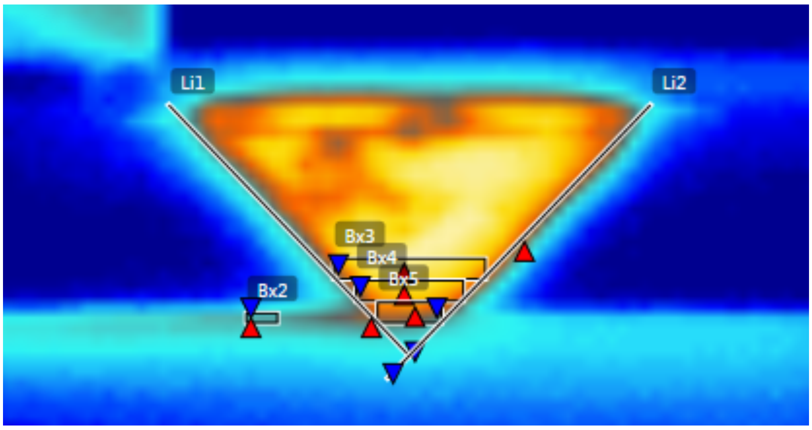


Figure 7 - IR image of extruder during print showing areas in which temperatures were measured

TABLE 3 - MEASURED TEMPERATURE FLUCTUATIONS DURING PRINT

	Mean (^{o}C)	Range (^{o}C)
Bx2 - Deposited filament	99.08	4.1
Bx3 - High nozzle	196.87	2.2
Bx4 - Mid nozzle	186.03	2.4
Bx5 - Nozzle Exit	150.92	4.8

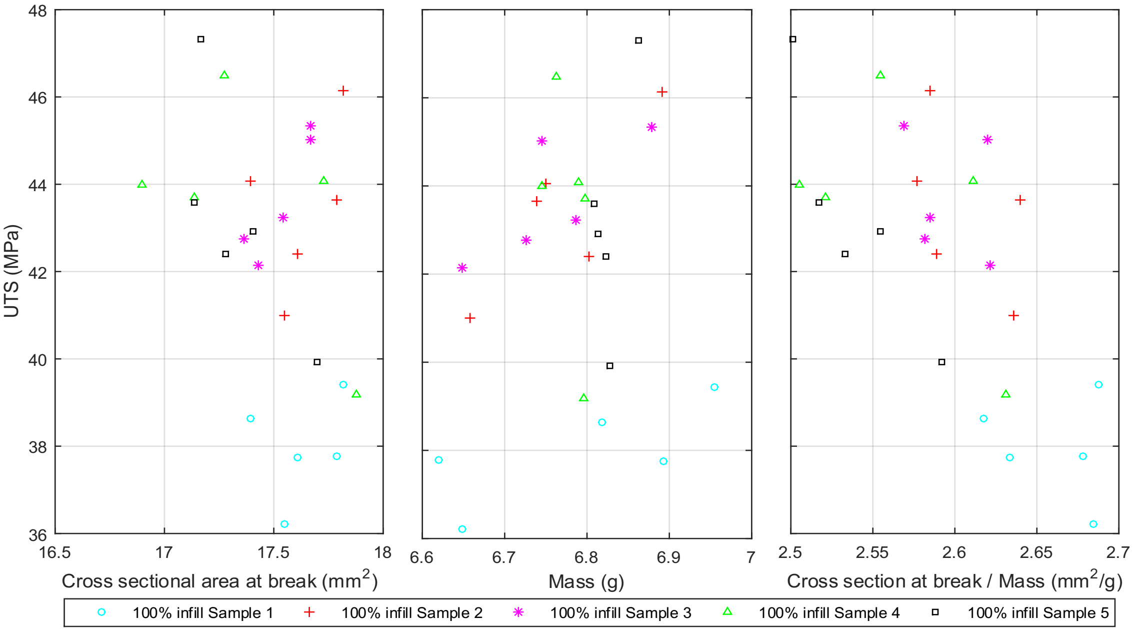


FIGURE 8 - SCATTER PLOT SHOWING STOCHASTIC RELATIONSHIP BETWEEN UTS AND OTHER PART PROPERTIES

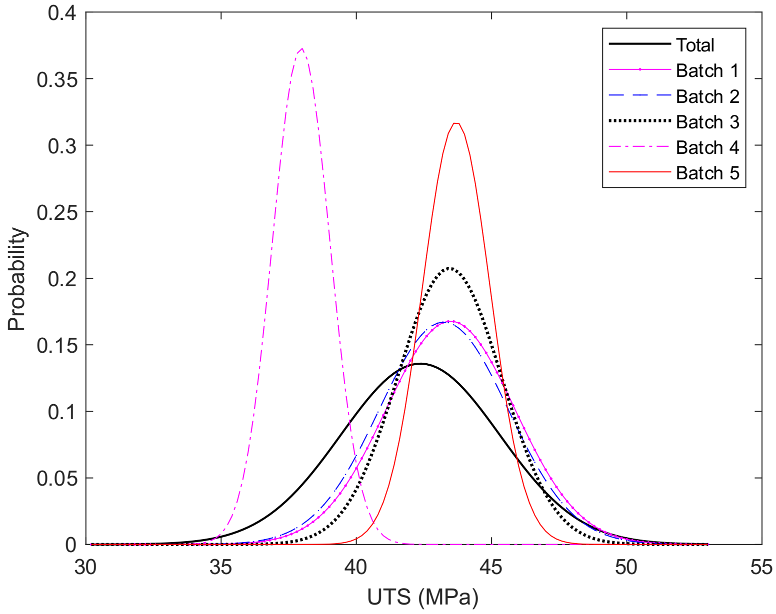


FIGURE 9 – PROBABILITY DENSITY FUNCTIONS FOR UTS OF 100% INFILL SPECIMENS

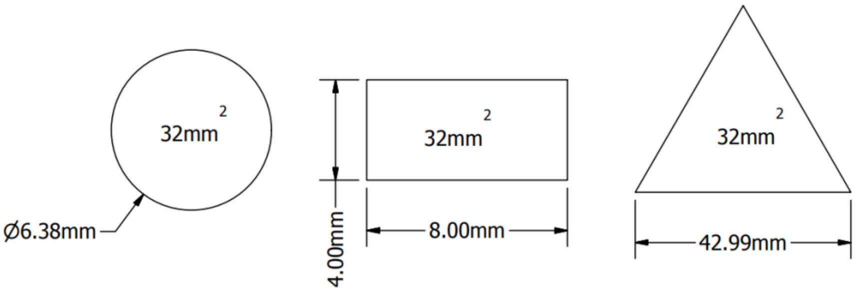


FIGURE 10 - SAMPLE CROSS SECTIONS FOR DETERMINING EFFECT OF SHAPE

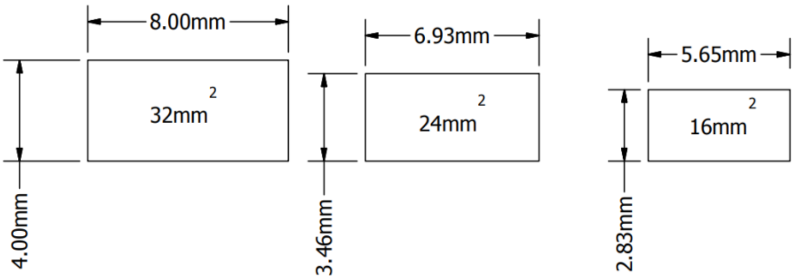


FIGURE 11 - CROSS SECTIONS OF TESTED SAMPLES FOR DETERMINING EFFECT OF SCALE.

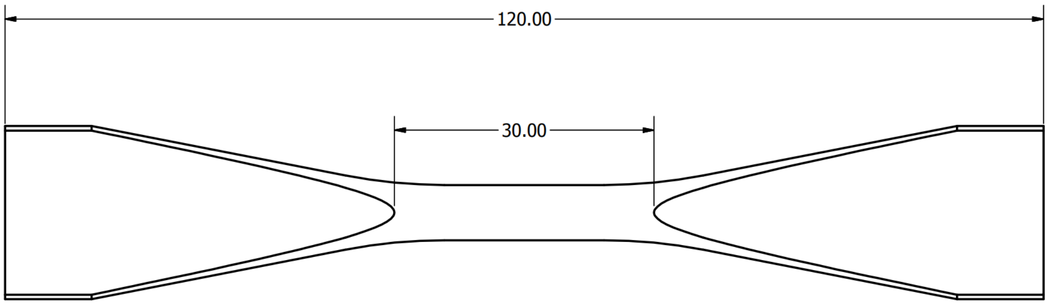


FIGURE 12 - DIMENSIONS OF TEST SPECIMEN FOR SHAPE & SCALE TESTING

Table 4 - Results of Tensile Testing to explore the effects of shape and scale. Standard Deviation is abbreviated to SD, percentage range is defined as the range divided by the mean expressed as a percentage. Baseline refers to sample 4.

Sample	**1**	**2**	**3**	***4***	**5**	**6**
Scale	¾	½	½	***1***	1	1
Top/Bottom layer thickness & number of solid shells (mm)	0.8	0.4	0.8	***0.8***	0.8	0.8
Cross Section Shape	Rectangle	Rectangle	Rectangle	***Rectangle***	Circle	Triangle
Break Load (N)	800.5	382.9	604.6	***876.4***	906.4	956.7
% difference when compared to control	*-9%*	*-56%*	*-31%*	***N/A***	*3%*	*9%*
SD (N)	27.4	7.7	23.5	***29.4***	39.0	37.4
Range (N)	75.3	16.9	65.2	***80.2***	107.9	85.1
% Range	9%	4%	11%	***9%***	12%	9%
Area (mm^2)	24.0	16.0	16.0	***32.0***	32.0	32.0
% difference when compared to control	*-25%*	*-50%*	*-50%*	***N/A***	*0%*	*0%*
UTS (MPa)	33.4	23.9	37.8	***27.4***	28.3	29.9
% difference when compared to control	*22%*	*-13%*	*38%*	***N/A***	*3%*	*9%*

Table 5 - Effect of Scale on ratio of infill to solid shell

Sample	**Cross section area (mm^2)**	**Top/bottom layer & Solid Shells**	**Shell Area (mm^2)**	**Infill Area (mm^2)**	**Ratio shell:infill**	**Break Load (N)**
4	32.0	0.8	16.6	15.4	1.08:1	876.4
1	24.0	0.8	14.1	9.9	1.42:1	800.5
2	16.0	0.4	6.1	9.8	0.62:1	382.9
3	16.0	0.8	11.0	5.0	2.21:1	604.6

Table 6 - Effect of shape on ratio on infill to solid shell

Sample	**Cross section area (mm^2)**	**Shape**	**Shell Area (mm^2)**	**Infill Area (mm^2)**	**Ratio shell:infill**	**Break Load (N)**
4	32.0	Rectangle	16.64	15.36	1.08:1	876.4
5	32.0	Circle	17.97	14.03	0.78:1	906.4
6	32.0	Triangle	16.03	15.97	1:1	956.7

Table 7 - How manufacturing parameters are incorporated into an FDM capability profile. Row colours correspond to parameter group

Parameter	Affects material property?	Affects sliced geometry?	Indicative trend from literature	Parameter Group
Layer Height	Yes. Increase in layer height increases strength	Yes - Vertical dimensions are discretised in increments of layer height	Linear increase (Alafaghani *et al.*, 2017)	3
Build Orientation	Yes - properties vary in different orientations	Yes - Directional discretisation varies depending on build direction	Discrete (Alafaghani *et al.*, 2017)	3
Raster Angle	Yes – greater strength when raster is in direction of applied load	-	Linear increase (Onwubolu and Rayegani, 2014)	1
Raster Width	-	Yes – affects solid shells as these must be in increments of raster width	Linear increase (Onwubolu and Rayegani, 2014)	2
Infill Pattern	Yes – gives varied properties in different directions	-	Discrete (Alafaghani *et al.*, 2017)	1
Infill Percentage	-	Yes – affects amount and distribution of material	Linear increase (Alafaghani *et al.*, 2017)	2
Top/Bottom Layers	-	Yes – affects amount and distribution of material	Quadratic / Quartic	2
Solid Shells	-	Yes – affects amount and distribution of material	Quadratic / Quartic	2
Extrusion Temperature	Yes – affects quality of raster adhesion	No	Parabolic (Alafaghani *et al.*, 2017)	1
Material Type	Yes – distinct properties for different materials	-	Discrete (Wittbrodt and Pearce, 2015)	1
Variability	Yes – distribution distinct for printers and materials	-	Normal Distribution Section 5.2.3	1
Geometry	-	Yes – affects ratio of solid shell & top/bottom layers to infill	Quadratic / Quartic	2

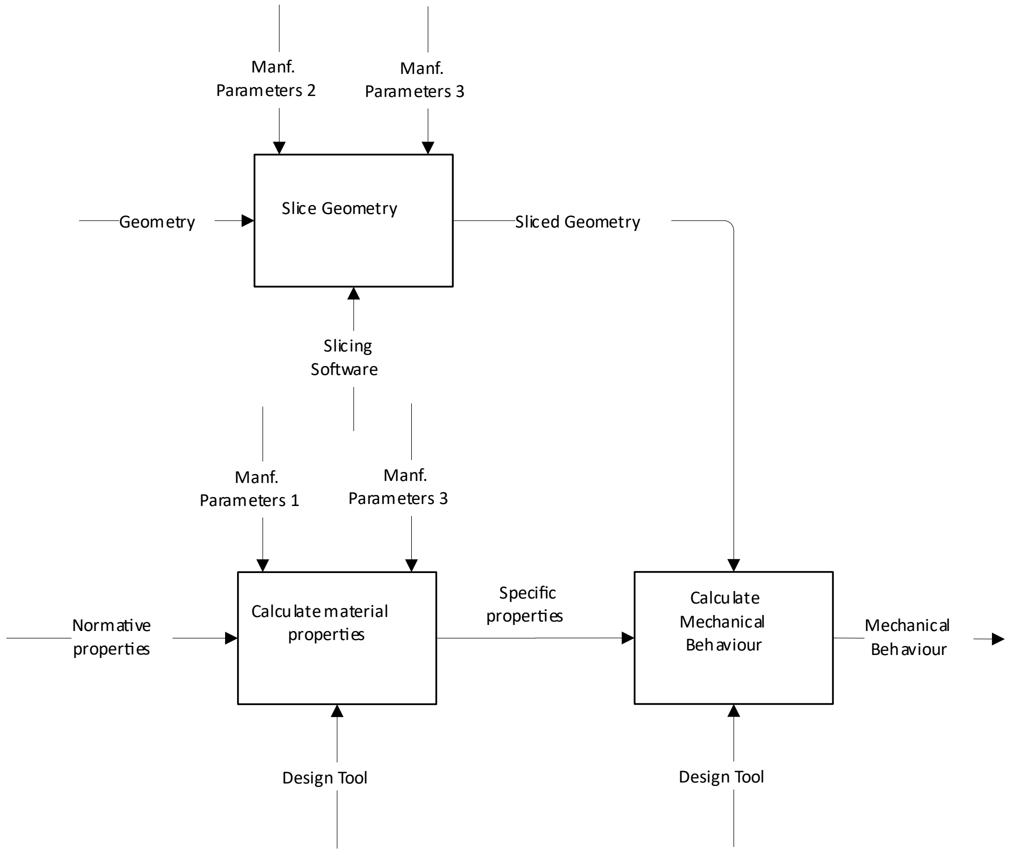


Figure 13 - IDEF0 diagram of how capability profile uses manufacturing parameters to calculate mechanical behaviour