# DESIGN FOR SCALABILITY AND STRENGTH OPTIMISATION FOR COMPONENTS CREATED THROUGH FDM PROCESS

**Qureshi, A.J.; Mahmood, Shahrain; Wong, W.L.E.; Talamona, Didier**
Newcastle University, United Kingdom

## Abstract

Design scalability is a technique used in routine design and manufacturing to adapt existing design knowledge to varying requirements. Guidelines exist for design scalability for subtractive manufacturing but there is much less support for components produced through additive manufacturing process. Due to particularities of additive manufacturing many process parameters related to additive manufacturing need to be taken into account while designing the parts with an expected functional requirement. The objective of the investigation described in this paper is to evaluate the effect of using design scalability technique for the 3D printed components with a focus on mechanical properties of the design. This is done through identifying and aggregating a list of comprehensive process parameters from research and available 3D printing machines, and then developing a standard based Taguchi's design of experiment to analyse the effect of these parameters, including scalability on the mechanical properties of an ISO compliant test sample for ultimate tensile stress and Elastic Modulus. A list of optimised parameters is also presented for achieving high tensile properties in 3D printed components.

**Keywords**: Design for X (DfX), Concurrent engineering (CE), 3D printing, Optimisation, Design for Scalability

**Contact**:
Dr. Ahmed Jawad Qureshi
Newcastle University
School of Mechanical & Systems Engineering
Singapore
ahmed.qureshi@newcastle.ac.uk

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## 1 INTRODUCTION

Additive Manufacturing (AM) refers to a manufacturing technology that produces physical parts from a 3-dimensional computer aided design (CAD) models to produce work pieces by depositing materials in successive layers without the need of any conventional tooling. Over the years, various method of the AM technology have been developed and this includes Stereolithography (SLS), Selective Laser Sintering (SLS), 3-Dimensional Printing (3DP) and Fused Deposition Modelling (FDM) processes (Wong & Hernandez 2012). The AM process is commonly used to produce prototypes due to its relatively short build time, low cost and simple operation.

Fused Deposition Modelling (FDM) is an AM process in which plastic material such as acrylonitrile butadiene styrene (ABS) or polylactic acid polymer (PLA) is fed to a heated nozzle. The semi molten plastic material is then extruded through a nozzle and deposited on a platform. A three dimensional solid component is built through bonding and solidifying the extruded layer with the previous layer. A typical FDM printer allows movement in the Z axis for the platform and in the X and Y-axis for the extruder nozzle.

With advances in additive manufacturing, low cost prosumer grade FDM printers such as the Makerbot Replicator 2X, Ultimaker 2 and 3D Systems Cube X available in the market. These printers are reasonably priced below USD$3000.00 and typically have a layer resolution of between 0.02mm to 0.2mm thick and build volumes ranging from (246x152x155) mm for the MakerBot Replicator 2x to (265x273x240) mm for the 3D Systems Cube X. Technical specifications of these prosumer grade FDM printers are comparable to professional grade FDM printers, such as the Stratasys Mojo Desktop 3 printers, which cost around USD$10,000. The Mojo Desktop 3 printer has a layer resolution of 0.178mm and a build volume of (127x127x127) mm. However, the cost of ownership for professional grade FDM printers is much higher when compared to the prosumer grade FDM printers.

With the lower initial cost of ownership, small and medium sized enterprises (SME) can build prototypes for basic functional testing of products under development. Besides the low cost of ownership, shorter manufacturing time and the possibility of printing complex structures without the need of any conventional or intermediate tooling are some of the benefits of the FDM technology. This relieves the SME's of the financial burden of acquiring expensive subtractive manufacturing equipment or outsourcing as well as the long-time delays associated with outsourcing, increasing the productivity and shortening the prototyping stage of the design process. However, FDM suffers from quality variation and unpredictability in dimensional accuracy, build volume, surface finish and strength of component (Noy 2005) even for the professional grade FDM printers.

This paper focuses on the strength of the printed component and presents a design method that:

- Establishes a guideline for part scalability while taking into account the mechanical properties of printed components
- Includes a comprehensive 13 factor list of process and machine parameters for printing ABS based components through common FDM printers
- Based on Taguchi's design of experiments, presents a ranking of critical factors affecting the mechanical and scalability properties of the printed components
- Provides guidelines for robust parameter optimisation for FDM built components through optimisation of process parameters available in the FDM machine

The FDM machine used in this investigation is the Makerbot Replicator 2x, which includes a building software, Makerbot Desktop for scaling and manipulating of the component's process settings. The feed material used is 1.75mm (diameter) ABS filament.

## 2 STATE OF THE ART

Over the years, research has been done to manipulate machine process factors to investigate the effect on mechanical properties of FDM printed parts. Sood et al. (2010) studied the influence of five process factors (layer thickness, build orientation, raster angle, raster width and air gap), with three levels assigned to each process factor, on the tensile properties on printed parts conforming to the ISO 527:1966 standard specimen. Three specimens were printed for each experimental run. The author's result for the tensile strength of the printed parts ranged from about 9 MPa to 18 MPa. Similarly Alhubail (2012) in his thesis carried out tensile test of FDM printed parts using five variable factors (layer thickness, raster width, contour width, raster orientation and air gap) with a ISO 527:1996 compliant standard component with two levels assigned to each of the factor. He concluded that the certain combinations of the process parameters can improve the tensile strength of printed parts (from a low of about 19 MPa to 36MPa). Ziemian & Sharma (2012) investigated the effect of four different raster angle orientations (longitudinal, diagonal, transverse and criss-cross) on the mechanical properties of an ASTM D3039 (ASTM, 1998) compliant printed part. Between five to ten specimens were printed for each experimental run. The authors concluded that printed parts with raster aligned with long dimension (longitudinal or 0°) of the specimen had the highest Ultimate Tensile Strength (UTS), about 25 MPa, while transverse raster orientation, 90° or perpendicular to the long dimension, had the lowest UTS, about 14 MPa. Fatimatuzahraa et al. (2011) conducted a similar study on the effect of raster angle with two orientations (criss cross at 0°/90° and criss cross at 45°/-45°, to the length of the specimen). Three rectangular specimens measuring 80mm (length) by 10mm (width) by 4mm (thickness) were tested. The author's finding was that 0°/90° orientation has a slightly higher tensile strength compared to the 45°/-45° orientation. Górski et al. (2013) studied the effects of build orientation with five different X and Y orientation sets, with respect to the build plate, to the material properties. Three ISO-527 compliant parts was printed for each experimental run. The tensile strength was the highest in the X=90° and Y=0° (side) orientation, about 22 MPa, and lowest in the Y=90° (vertical) orientation, about 11 MPa. Tymrak et al. (2014) studied the effects of two variable factors, layer orientation and raster orientation, with three and two levels respectively. Ten specimens conforming to ASTM: D638 standards was printed and tested. His findings was the average tensile strength was higher for smaller layer heights and parts printed with raster orientation 0°/90° yield higher strength compared to the 45°/-45° raster orientation. Ahn et al. (2002) had five variable factors (air gap, raster width, extruder temperature, raster orientation and filament colour) with two levels for each factor. Each experimental run consist of three to five specimens printed to the ASTM D3039 (ASTM, 1976) standards. The author concluded that air gap and raster orientation factors greatly affect the tensile strength of printed parts whereas the other three factors (raster width, extruder temperature and filament colour) showed little effect on the material property.

*Table 1. Common process parameters used in Material Strength of FDM Printed Parts*

| | Reported process parameters | | | | | | | | Reported Properties | |
|---|---|---|---|---|---|---|---|---|---|---|
| Factors / Authors | Layer Thickness | Build Orientation | Raster Angle | Raster Width | Air gap | Contour Width | Extruder Temperature | Filament Colour | Average UTS (MPa) | Elastic Modulus (MPa) |
| (Sood et al. 2010) | ✔ | ✔ | ✔ | ✔ | ✔ | | | | | |
| (Alhubail 2012) | ✔ | | ✔ | ✔ | ✔ | ✔ | | | | |
| (Ziemian & Sharma 2012) | | | ✔ | | | | | | 18.96 | 809.09 |
| (Fatimatuzahraa et al. 2011) | | | ✔ | | | | | | 18.41 | |
| (Górski et al. 2013) | | ✔ | | | | | | | | |
| (Tymrak et al. 2014) | ✔ | ✔ | | | | | | | 28.53 | 1811.23 |
| (Ahn et al. 2002) | | | ✔ | ✔ | ✔ | | ✔ | ✔ | | |
| (Bertoldi & Yardimci 1998) | | ✔ | | | | | | | 12.37 | 1355.75 |
| (Montero et al. 2001) | | | ✔ | ✔ | ✔ | | ✔ | ✔ | 15.20 | |
| (Novakova-marcincinova & Novak-marcincin 2013) | No factors mentioned | | | | | | | | | |

Bertoldi & Yardimci (1998) concluded that build orientation (one factor) greatly affects the tensile strength of FDM printed parts. Specimens designed to conform to ASTM D5937-96 standard for moulded plastics parts was printed and tested. The UTS for specimens printed on the side orientation yielded the highest result for X=90° and Y=0° and lowest when printed in the vertical orientation. This finding was similar to that of (Górski et al. 2013). Novakova-marcincinova & Novak-marcincin (2013) investigated the mechanical properties of FDM printed parts though there was no mention of variable factors used.

Based on the above literature reviews, it is observed that varying the machine process factors will have an effect on the mechanical properties of FDM printed parts. However, none of the existing research work address scalability as well as a comprehensive list of parameters representative of options available in prosumer grade printers, from the printer accompanying slicer software, which can be varied to study the full effect on the mechanical properties of the FDM printed parts. Furthermore, limited number of samples were tested over subsets of a wide range of known and communicated set of parameters, which does not allow taking into account variations within a given sample population and its variance characteristics methodology. A majority of the research work only provides information about mean values of the UTS on a given default values of process parameters and do not undertaking the study of effect of parameter change on the strength of the samples as well as scalability of component.

Uncertainty is ubiquitous in any engineering system at any stage of product development and throughout a product life cycle (J. Y. Dantan et al. 2013). This is ever more apparent in the FDM processes in prosumer grade printer due to a multitude of factors. It is therefore important to study the effect of variation in the process parameters for the FDM process on the quality and robustness of the printed components while considering scalability. This paper addresses this by presenting a Design of Experiments based method for evaluating the effect of process parameters and scalability on strength of the printed samples with an example to tensile strength property. The following sections provide, a method for designing an experiment with Taguchi's design of experiment for a comprehensive list of process parameters for a tensile test sample, the experimental results of the samples obtained as per the relevant ISO standards, and a discussion and conclusion on the important factors and their effect on the UTS and elastic modulus of the test samples.

## 3 METHODOLOGY

A systematic methodology based on the literature review, process parameters of FDM process, and Taguchi's design of experiment is developed which is applicable to a majority of FDM based 3D printer machines. The approach developed by Taguchi is a frequently used statistical method for robust design in literature (Bergman et al. 2009). It is also a systematic and efficient methodology for design optimisation and is widely used for product design and process optimisation worldwide (Lee et al. 2005; Beyer & Sendhoff 2007; Taguchi et al. 2005).Taguchi's technique allows for simplification of experimental plan and feasibility of study of interaction between different parameters resulting into fewer number of experiments and reduced time and costs. This is especially vital for rapid prototyping where cost to produce prototypes is still high. Taguchi proposes experimental plan in terms of orthogonal array that gives different combinations of parameters and their levels for each experiment. According to this technique, the entire parameter space is studied with minimal number of necessary experiments only (Kacker et al. 1991). Based on the average output value at each parameter level, main effect analysis is performed. Analysis of variance (ANOVA) is then used to determine which process parameter is statistically significant and the contribution of each process parameter towards the output characteristic. With the main effect and ANOVA analyses, possible combination of optimum parameters can be predicted.

The methodology adopted in this paper comprises the following major activities: review of the literature to identify commonly used process parameters and their values; comparison of the research parameters and their values with a common set of process parameters available for popular prosumer grade printers; development of a comprehensive design of experiments containing an essential list of parameters including component scaling and a range of parameter values to be tested; Printing and testing of the components for tensile strength; and identification of critical parameters and their optimised values.

### 3.1 Design of Experiment for Mechanical Testing

As discussed in the state of the art and shown in the matrix of parameters showing the parameters analysed in the earlier research works (Table 1), a comprehensive list of process parameters that encompasses the category of the prosumer grade printers and associated software is required. This is done through identification of 13 controllable factors, process factors which can be varied via the printer accompanying slicer software, which may affect the material properties of FDM printed parts. These factors are based on a consensual aggregation of the factors presented in the earlier researched works as well as the most common controllable factors available in popular STL to slicing and printing software. Taguchi's method of Design OF Experiment (DOE) is used to investigate the 13 factors with the three level responses on the tensile properties of the printed parts. According to (Taguchi et al. 2005), in order to analyse the effect of 13, three-level factors, a L27 factorial design is required which was selected based on 13 factors and three levels of experiment. Table 2 summarizes the factors identified and the control levels.

*Table 2. Factors and Control Levels*

| No | Factor | Level 1 | Level 2 | Level 3 |
|---|---|---|---|---|
| 1 | Component Scale (thickness *h*) | 2 mm | 4 mm | 6 mm |
| 2 | Print Location (on Buildplate) | Left | Center | Right |
| 3 | Extruder Temperature (°C) | 218.5 | 230 | 241.5 |
| 4 | Print Orientation (°) | 90 | 45 | 0 |
| 5 | Speed while travelling (mm/s) | 120 | 150 | 180 |
| 6 | Speed while extruding (mm/s) | 72 | 90 | 108 |
| 7 | Buildplate Temperature (°C) | 104.5 | 110.0 | 115.5 |
| 8 | Peeling Temperature (°C) | 38.0 | 40.0 | 42.0 |
| 9 | Layer Thickness (mm) | 0.16 | 0.20 | 0.24 |
| 10 | Infill Density | 8% | 10% | 12% |
| 11 | Number of Shell | 1 | 2 | 3 |
| 12 | Infill Pattern | linear | hexagonal | moroccanstar |
| 13 | Infill Shell Spacing | 0.64 | 0.80 | 0.96 |

### 3.2 Experimental Setup

Test specimens conforming to ISO-527-1/2:2013 Type 1BA [ISO527 standard] were used to determine the tensile properties of the FDM printed parts. Using the dimensions from the ISO standard (*Figure 1*), a solid model was created in Autodesk Inventor 2015 and exported in form of a .STL file. Due to three different levels of thickness scaling, the level 1 dimensional scale was chosen to be the standard ISO527 1BA sample, whereas the Level 2 and Level 3 scaling refer to 100% and 200% increase in the smaller initial dimension *h* of the rectangular cross-section in the central part of the test specimen. The file was then processed in accordance with the parameter configuration as per L27 Array using the MakerBot slicing software MakerWare. The parts were printed using MakerBot replicator 2X using the OEM MakerBot ABS material. The standard physical properties of the MakerBot ABS as provided by the manufacturer, corresponding to standard print settings are given in Table 3 (MakerBot n.d.).

*Table 3. MakerBot ABS OEM Strength Data (MPa) as per ASTM Standards (no.)*

| Tensile (D638) | Flexural (D790) | Compressive (D695) |
|---|---|---|
| 34.02 | 36.84 | 7.58 |

The L27 array calls for 27 unique configurations for the parameter levels. Each of these configurations was printed 3 times under same environmental positions in order to ensure the consistency of uncontrollable factors. The total population size therefore is 27*3=81 samples.The tensile test was conducted using Instron 5980 Universal Testing System at a constant crosshead displacement. Three specimens were printed and tested for each experimental run. The data of load (N) and extension (mm) was recorded and used to compute the Ultimate Tensile Strength (UTS) and Elastic Modulus $E_t$ of the printed parts. The data was electronically collected and comprised of more than 4000 data points per sample tested.

# 4 EXPERIMENTAL RESULTS

The data collected from Taguchi's L27 orthogonal test array was analysed and ranked for: signal to noise ratio with selection of 'larger is better' signal to noise ratio; factor analysis for the means of the factors; and an overall analysis of the mechanical tensile properties for the population representing a mix of factor value variation over three levels as per L27 Array.

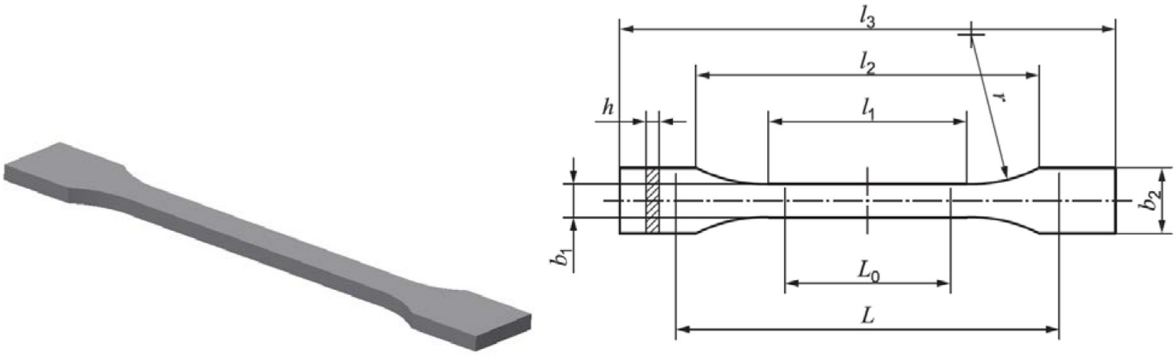


*Figure 1. CAD design of ISO-527-1/2:2012 Type 1BA Test Specimen and its scale*

## 4.1 Population UTS and Elastic Modulus Characteristics

The overall UTS and elastic modulus characterises of the population n=81 are shown in Figure 2. For n=81, the maximum and minimum values obtained for UTS were 28.89 and 10.86 MPa respectively, including the control parameters corresponding to the MakerBot's standard settings (MakerBot n.d.), which fall short of the standard strength values as published by the manufacturer . This indicates a reduction of between 15-70% due to a combination of 13 factor variations and differences in specimen size because of different testing standard. The population UTS mean is 18.80 MPa with $\mu = 18.80$MPa and $\sigma = 4.68$MPa with all the samples being within ±2σ. The population is divided in 27 batches of three samples each with each batch corresponding to a row in the L27 array. Figure 3 shows the histogram related to the standard deviation of samples in batches. It can be noted that the mean of the sample standard deviations is centred on 0.52MPa with $\sigma = 0.41$MPa, with most of the batches exhibiting standard distribution in the range of ±1σ and all of the standard deviations but one within ±3σ. It is clear from these figures that the variation within the batch for fixed parameter is significantly less (2% average) than the variation within the population. The mean UTS value obtained in this study correlates with the UTS values reported in earlier research works by Ziemian & Sharma (2012) and Montero et al. (2001) (Table 1).

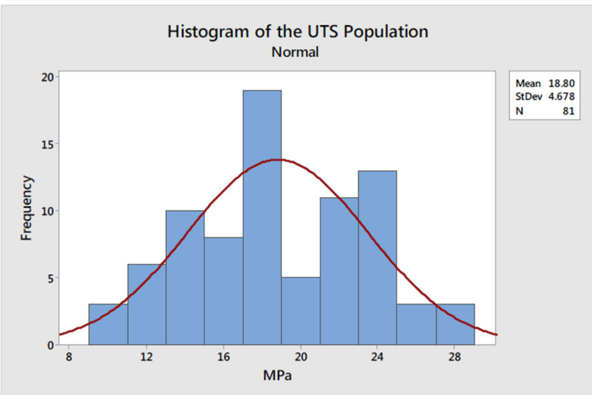


*Figure 2. population UTS*

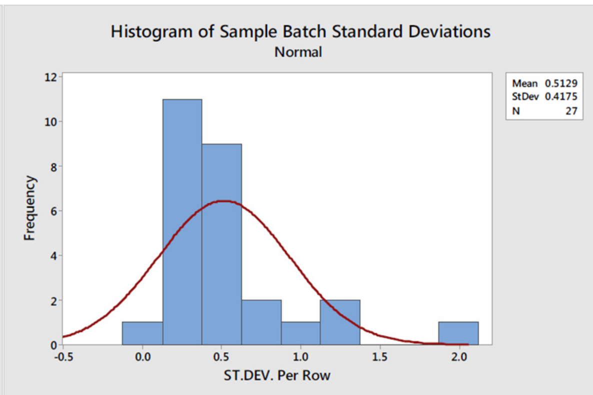


*Figure 3. Batch UTS Standard Deviations*

Similar to UTS, the Elastic Modulus of all the samples was measured. This was done by finding the slope of a linear least-squares regression line in the strain interval $\varepsilon_1$ = 0,05 % and $\varepsilon_2$ = 0,25 %. The elastic modulus of the population n=81 varies between 447.4-935.5 MPa $\mu$= 666.5MPa and $\sigma = 147.9$ MPa for all the different permutations of the L27 array (Figure 4). The adverse value of standard deviation is due to the varying process parameters of L27 array. However, similar to the observation of the standard deviation within the samples printed with same parameter configuration for UTS, the standard deviation within the samples printed with same settings was found to vary between the limits of 1.08-104.6 MPa, $\mu$= 23.43MPa, and $\sigma = 23.92$ MPa (Figure 5). Majority of batches (n=23 of 27) have sample standard deviation less than 30MPa. Consistent with UTS plots, the standard deviation within the sample batches is significantly reduced with an average of 3.4% of sample mean Modulus.

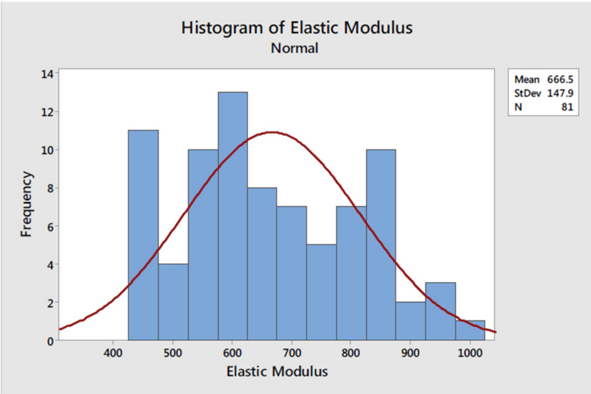


*Figure 4. Population Elastic Modulus $E_t$*

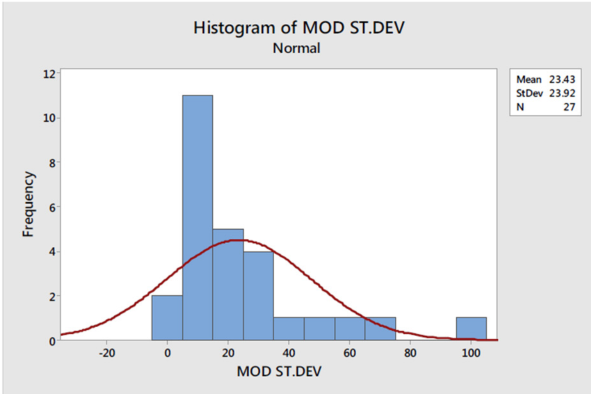


*Figure 5. Batch Modulus Standard Deviations*

## 4.2 Factor analysis for UTS and Elastic Modulus Characteristics

In order to find the influence of the factors on the UTS and $E_t$, Signal to Noise ratios for the each factor as well as the effect of factors on mean values was found. Table 4 shows the ranking based on signal to noise ratio for the factors. The formula for 'larger is better' signal to noise ratio was used to analyse the factor influence. Some interesting observations can be made from the results. It is observed that the scaling size on the thickness dimension has the highest signal to noise ratio, followed by no. of shells, and print orientation. Using the cumulative delta of all the factors as a relative measure (14.06), it becomes clear that the top three factors contribute to 60 percent of the response in signal to noise ratio.

*Table 4. Response Table for Signal to Noise Ratios (Larger is better)*

| | Parameter No. (from Table 2) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Level | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
| 1 | 27.29 | 25.37 | 25.21 | 25.01 | 25.11 | 25.71 | 25.11 | 25.36 | 25.43 | 25.45 | 23.63 | 25.34 | 25.71 |
| 2 | 24.73 | 24.86 | 25.19 | 25.92 | 25.52 | 25.06 | 25.74 | 24.8 | 24.65 | 24.94 | 25.44 | 25.35 | 24.97 |
| 3 | 23.58 | 25.36 | 25.18 | 24.66 | 24.96 | 24.82 | 24.74 | 25.43 | 25.52 | 25.2 | 26.53 | 24.9 | 24.92 |
| Delta | 3.71 | 0.51 | 0.03 | 1.26 | 0.55 | 0.88 | 1 | 0.62 | 0.87 | 0.5 | 2.9 | 0.44 | 0.79 |
| Rank | 1 | 10 | 13 | 3 | 9 | 5 | 4 | 8 | 6 | 11 | 2 | 12 | 7 |

Table 5 presents the factor response table for mean values of the UTS. The findings of the mean values rank the factors according to their significance on the mean UTS value of the samples. The three most significant factors identified are identical to factors in the response table for signal to noise ratio. They are: component size or scale, no. of shells, and print orientation. It is evident that increasing the scale of the thickness factor has a negative effect on the UTS of the printed component. This interesting observation is contradictory to the traditional subtractive manufacturing process where change in the scale for a material does not have a significant effect on the UTS of the material. The main factor responsible for this is that as the component is manufactured with a fill density varying from 8-12%, and as the component size increases, the ratio between the shells, floor and roof of the sample, which constitute a 100% fill, and the infill becomes smaller, leading to more voids within the component, thereby decreasing its mechanical property. On the other hand increasing the no. of shells results into an increase in the UTS of the test sample. For components of the same component size, increasing the number of shells improves the UTS due to an increase in the thickness of the wall of the specimen.

*Table 5. Response Table for Means*

| | Parameter No. (from Table 2) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Level | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
| 1 | 23.43 | 19.02 | 18.78 | 18.36 | 18.56 | 19.8 | 18.71 | 19.29 | 19.39 | 19.34 | 15.87 | 18.9 | 19.52 |
| 2 | 17.53 | 18.16 | 18.92 | 20.13 | 19.62 | 18.78 | 19.88 | 17.76 | 17.64 | 18.12 | 19.05 | 19.01 | 18.53 |
| 3 | 15.45 | 19.23 | 18.72 | 17.92 | 18.23 | 17.83 | 17.82 | 19.36 | 19.37 | 18.95 | 21.48 | 18.49 | 18.36 |
| Delta | 7.98 | 1.07 | 0.2 | 2.2 | 1.4 | 1.96 | 2.06 | 1.6 | 1.75 | 1.22 | 5.61 | 0.52 | 1.17 |
| Rank | 1 | 11 | 13 | 3 | 8 | 5 | 4 | 7 | 6 | 9 | 2 | 12 | 10 |

Lastly the print orientation also plays a significant role in the UTS of the component. The angle corresponding to 90 degree, which aligns the raster direction with the axis of the tensile tests results into a higher UTS as opposed to the horizontal (0 degree), which results into a transverse angle between the axis of the tensile test and the raster pattern. The results are consistent with those of fibre-reinforced composites where the largest contribution to strengthening is obtained when fibres are oriented in the direction of the axis for tensile testing. The effects of the factors on the means are graphically presented in Figure 6 from where the effect of other parameters on the UTS can be observed. It is evident from the figure that the cumulative effect of the three top ranked parameters significantly outweighs the cumulative effect of the rest of the parameters.


*Figure 6. Main Effects Plot for Means*

Using the component size, no of shells and print orientation parameters, Figure 7 provides a Box plot with nested grouping in terms of above parameters of all the population of test samples. A clear clustering effect can be noted in the box plot based on the parameter nesting. The mean UTS of the clusters shows a decreasing trend with increase in the component size factor, whereas the general shape of all the clusters show a significant skew within the cluster due to effect of no of shells, i.e., the samples with higher no. of shells appearing towards the peak of the clusters and the samples with lower no. of shells appearing towards the tail of the clusters. In order to study the effect of the print orientation in relation to the component size and no of shells, a bubble plot between UTS and Et with grouping is presented in Figure 8. It can be noted from the plot that the samples with 90 degree print orientation provide the highest UTS. On the other hand, the samples with transverse or 0 degree raster provide the lowest mean UTS. This is due to alignment of the raster with the tensile test direction.

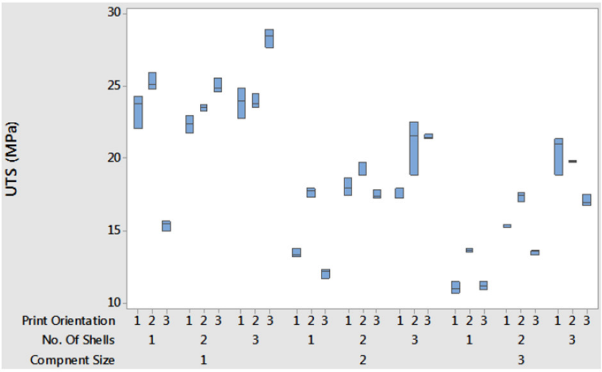


*Figure 7. Box Plot for UTS vs $E_t$*

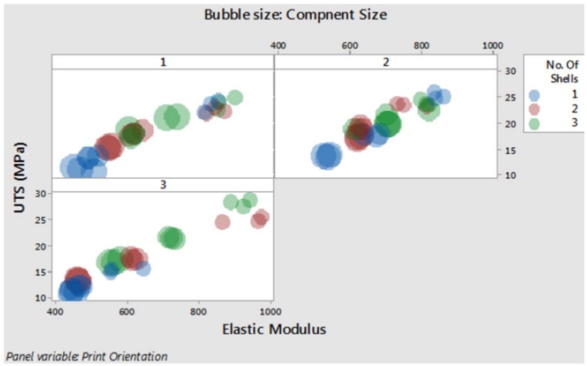


*Figure 8. Bubble Plot for UTS vs $E_t$*

## 5 DISCUSSION

In a conventional manufacturing operation, for a fixed shape and a fixed manufacturing process, for a given material, the mechanical properties are independent of the scale of the component, i.e. for a rectangular cross section, considering all the factors except the scale of the dimensions to be constant, a mechanical property such as tensile strength of a sample is not expected to drastically deviate from the one scale to another. However, as the results in this paper show, it is not true for components created with additive manufacturing, specifically for FDM processes. In the FDM process, the product shape as well as mechanical properties is intricately linked to each other through the different process parameters. Building upon the existing work, this paper shows that the scale of the component is an important parameter affecting the mechanical property of the printed component inversely.

The FDM design and manufacturing process depends on a number of parameters which can be divided into slicing software settings, machine parameters, and component geometry parameters. A number of these parameters have been discussed and recorded in the earlier research works. However, in order to insure repeatability and consistency of component mechanical properties, a more comprehensive study is necessary to investigate the effects of the main factors mentioned earlier on the mechanical properties of printed parts.. This is evident from Table 5 which shows the mean effects of the parameters that changing the values of 13 parameters presented will affect the mechanical properties of the printed sample. The matrix proposed in this paper provides a comprehensive set of parameters which can be used to control the quality of printed components. Using the DOE, the optimised values for the parameters were also found for UTS which is shown in Table 6. The setting values of each parameter correspond to the setting values as given in Table 2.

With the optimised print parameters, end-users are able to use them as a guide when printing parts with mechanical strength in mind. Furthermore, since the factors considered in this paper are not printer specific, the optimised print parameters can be used in other prosumer grade FDM printers such as the Ultimaker and Reprap models.

*Table 6. Optimised Print Parameters*

| | Parameter No. (from Table 2) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
| Setting | 1 | 3 | 2 | 2 | 2 | 1 | 2 | 1 | 1 | 1 | 3 | 2 | 1 |

The results from DOE also give an indication of variability and uncertainty in the mechanical properties of the samples due to change in the process parameters. The difference between the values of indicator of the variability such as standard deviation of UTS as calculated across the population or within the batch demonstrate the importance of considering, recording and maintaining coherent process parameter selection during the design process to ensure the fulfilment of requirements and specifications related to mechanical properties. Using a formal frame work such as CPM-PDD (J. Dantan et al. 2013) or set based robust design (Qureshi et al. 2010) and meta modelling, this work can be further developed to propose a meta model to enable the designers to scale the 3D printed components and obtain the updated process parameters to enable a consistent robust mechanical property with scale to minimise variation and uncertainty in product.

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