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# A Design of Experiments Approach for the Optimisation of Energy and Waste During the Production of Parts Manufactured by 3D Printing

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**Abstract**

Direct digital manufacture and additive manufacture has expanded from rapid prototyping into rapid production and has the possibility to produce personalised high quality products with the batch size of one. Affordable additive manufacturing machines and open source software enables a wide spectrum of users. With a populace empowered with the possibility of producing their own products, this disruptive technology will inevitably lead to a change in energy and material consumption. With such an unpredictable impact on society it is timely to consider the economic and environmental issues of growth in this sector. This work demonstrates a Design of Experiments approach for part optimisation with a consideration of scrap weight, part weight, energy consumption and production time. The main conclusion of this study was that through optimisation of machine build parameters a desired response is possible and compromises between output responses such as scrap and production time can be identified. The research also showed that identical build parameters for different designs can yield different output responses, highlighting the importance of developing design specific models. The scientific value of the work lies in the contribution of new data sets for models in additive manufacturing. Together with the optimisation method adopted, the results allow for a more detailed and accurate assessment of the economic and environmental impact of 3D printed products at the design stage.

**Keywords**

Direct digital manufacture; Additive manufacturing; Design of experiments; Energy consumption; Process optimisation; Rapid prototyping; Rapid manufacture.

**Highlights**

- A Design of Experiments approach was used to optimise build parameters for 3D printed parts.
- Optimisation for single outputs such as energy consumption and waste output could be achieved.
- Compromises between objective responses could also be achieved.
- The approach could be used at the design stage to maximise efficiency in the production stage.
- The work could contribute to reduced environmental burden of the rapidly expanding sector.

## 1. Introduction

The industrial sector encompasses a diverse set of industries, including manufacturing (food, paper, chemicals, refining, iron and steel, nonferrous metals, non-metallic minerals, and others) and nonmanufacturing (agriculture, mining, and construction). This sector consumed about one-half (52%) of the world's total delivered energy in 2010, and its energy consumption grows by an average of 1.4% per year from 2010 to 2040 (International Energy Agency, 2013). On average, 16 tonnes of materials are used annually per person in the EU, and of the 6 tonnes of waste generated per person 13 % is from manufacturing (European Environment Agency, 2010). With such a high percentage, the manufacturing cost in relation to quality and productivity efficiencies is now a focus for environmental performance efficiency (Hon, 2005; Garetti and Taisch, 2012; Wang et al., 2014). Optimised production for energy waste is of utmost importance as it provides knowledge of overall state of the factory and its performance regarding energy consumption. In terms of energy and its relationship to the specification of the parts being manufactured, May et al., identified the following four considerations as important; Definition of the production system, Identification of different power requirements, Analysis of manufacturing states as causes of energy inefficiencies during manufacture and Linking manufacturing states with energy states (May et al., 2015).

The way products are now being produced is under a redefinition through Direct Digital Manufacturing (DDM). DDM is one of the new advanced manufacturing paradigms (Gibson et al., 2010), and it is now possible that part production can be moved from the traditional factory environment. Outside of the traditional manufacture, a growing number of products can be produced by Additive Manufacturing (AM) right at or close to the customer. DDM describes the process of using a 3D (CAD) model for direct-fabrication without the need for process planning (Gibson et al., 2010). At the core of DDM is AM. AM refers to a process during which a raw material is converted into a solid part on an additive, layer-by layer basis (Williams et al., 2011). AM technologies were initially focused on the production of complex geometry prototypes giving rise to the term 'rapid prototyping' (RP) (Hopkinson and Dickens, 2003). RP processes rely upon a digital representation as an input and produce a solid 3D part in a bottom-up layer-by-layer process (Williams et al., 2011).

The more recent move is towards applying these technologies to the production of end-use products termed 'rapid manufacturing' (Hopkinson and Dickens, 2003). It may seem counterintuitive to apply RP technology to the manufacture of higher volume parts as RP is unable to beat the considerably lower cycle times, and material and capital equipment costs of more traditional manufacturing methods such as injection moulding. Such limitations are however offset by reduced tool costs, reduced lead times and significantly enhanced design freedom for creating complex geometry parts offered by RP technologies (Hopkinson and Dickens, 2001). FDM is currently one of the most commonly used AM techniques (Onwubolu and Rayegani, 2014) and was introduced in 1992 by American company Stratasys (Boschetto and Bottini, 2013). Commercial FDM 3D printers allow for small-scale manufacturing or as an enabling tool for green manufacturing [Pham and Gault, 1998; Sood et al., 2009a).

Literature supports that process parameters largely influence the quality characteristics of AM parts. Many studies have been carried out to investigate and attempt to balance the ability to produce aesthetically pleasing products with functionality. Various works have looked at adjusting key parameters during fabrication in order to achieve improved mechanical properties, improved surface finish and improved dimensional accuracy. Sood, A. et al., (2009) considered the impact on tensile, flexural and impact strength of five key processing parameters namely layer thickness, orientation, raster angle, raster width and air gap. Response surface methodology was used to attempt to derive the empirical model between processing parameters and mechanical properties and also to assess the relative effect of each process parameter on the mechanical properties. Rayegani and Onwubolu (2014) and Onwubolu and Rayegani et al., (2014) investigated the functional relationship between the above same process parameters and the tensile strength of test specimens manufactured via FDM. Sood et al., (2001) attempted to optimise tensile, bending and impact strength simultaneously by investigating the effect of the same five key processing parameters. The multiple responses (tensile, bending, impact) are converted into a single response using principal component analysis (PCA) to eliminate the influence of correlation among the responses. The research indicates that all of the processing parameters and the interaction between layer thickness and orientation significantly influence the response. Optimum parameter settings were identified to simultaneously optimise tensile, bending and impact strength. An accepted limitation of the FDM process relates to the obtainable dimensional accuracy of the parts (Boschetto and Bottini, 2013). Sood et al., (2009a) reports upon experimental work carried out to investigate the influence on dimensional accuracy and interaction of the 5 key processing parameters. Sood et al., (2009b) also considered the effect of these parameters on the dimensional accuracy of FDM parts manufactured from ABSP400 (acrylonitrile-butadine-styrene). The study used grey Taguchi’s method to optimise the process parameters to minimise percentage changes in length, width and thickness of the part. Experimental work was used by Boschetto and Bottini (2013) to validate a geometrical model of the filament, dependent on the deposition angle and the layer thickness to allow prediction of obtainable part dimensions. Previous research recognises that compromises are often necessary between two contradictory aspects of parts manufactured via FDM, namely the surface finish requirements and the part deposition time. Thrimurthulu et al., (2004) applied a real coded genetic algorithm to optimise the part deposition orientation to both enhance the surface finish and reduce the build time. Anitha et al., (2001) assesses the influence of layer width, road width and speed of deposition on the quality of the prototype and uses Taguchi technique to attempt to optimise these process conditions with respect to minimizing the surface roughness of the part. Most significant was the layer thickness which was demonstrated to have a strong inverse relationship with surface roughness.

In the last century, focus was on the quality and functionality of parts as opposed to the environmental impact of the manufacturing process. Designers benefit from the flexibility of FDM in terms of material choice with specific materials available to meet functional, mechanical and aesthetic design requirements. With the ever increasing importance placed on sustainability, more focus is now being placed on environmental considerations (Mognol et al., 2006). This means that the design stage must consider constraints of time and cost and to furthermore consider sustainability and the need to seek to reduce scrap. Tang et al., (2016) integrated a design stage in a product life cycle assessment for minimizing the product environmental impact of AM process. In a case study between CNC and an AM fabrication process it was shown that the AM process consumes significantly less energy and produce less CO2 to produce the part than CNC milling for the same product. A smaller body of research exists to consider not just technological optimisation of FDM parts, but also the cost. Anitha et al., (2001) acknowledge that due to the high prototype cost, it is necessary to optimise the process parameters from both a technological and economic viewpoint to allow parts to be manufactured to meet required mechanical properties and within manufacturing cost constraints.

Additive layer manufacturing processes, such as FDM, based on material addition are generally accepted as more material efficient than alternative subtractive mechanical machining processes. The energy consumption of layered manufacturing processes is however relatively unexplored (Balogun et al., 2014). Huang et al., (2015) identified that the adoption of AM components in aircraft has the potential to provide significant energy savings, due to reduced material requirements needed for production and the fuel economy (reduction of 6.4%) from lighter weight components Alexander et al., (1998) identified two of the most basic challenges of all AM processes as being determination of the optimal build orientation and minimizing the manufacturing costs. Their work seeks to analyse the relationship in general terms so as to be applicable to a range of AM processes through the development of independent methods to consider build orientation and costings, allowing the output of each to be combined. A generic model for direct energy demand in layered manufacture was proposed by Balogun et al., (2014), focusing on and comparing three different FDM machines and also benchmarking against alternative mechanical manufacturing processes. Mognol et al., (2006) considered three AM processes including FDM, with respect to selecting a set of parameters to reduce the electrical energy consumption. The study found that there is no general rule that can be applied across technologies to optimise the electrical energy consumption. In terms of scrap and recycling in AM processing Kreiger et al., (2014) concluded that with the open-source 3-D printing networks the potential for widespread adoption of in-home recycling of post-consumer plastic represents a novel path to a future of distributed manufacturing with lower environmental impacts than current systems.

Limited research exists with the view of increasing the application potential of FDM by producing parts at minimum cost. Ingole et al., (2011) stated that an optimal build orientation ensures optimum utilization of resources and thus reduces the cost. Similarly, Raut et al., (2014) recognize that build orientation is a critical factor in FDM as it affects the material usage, build time, total cost per part and part mechanical properties. Ingole et al., (2011) developed a universal mathematical model to minimize the total manufacturing cost of different complex geometry parts using FDM. The experimental work considered tensile and flexural specimens manufactured via different build orientations and concluded that the build orientation does have a significant effect on the tensile strength, flexural strength and total cost of the FDM parts.

Layer based methods of manufacture such as 3D printing are the most disruptive production technologies used today. Function and quality has been the main focus off FDM research. With such an uptake of the technology it is important that physical tests are used to evaluate performance and reliability but they also have to be tested for quality combined with scrap rate (Chen et al., 2015) and that environmental factors are also considered. This research builds on work published on 3D printing optimisation for improving the mechanical properties of FDM Parts (Griffiths et al., 2016). The work is a starting point for the creation of a knowledge repository not just for optimising function, but with a focus on improving the energy and waste during production. It is hoped that the findings are a useful tool for designers in the selection of build parameters, where consideration goes beyond mechanical properties of their product but also the environmental and economic issues such as energy and material consumption. A DOE approach will be used for identifying opportunities in balancing part quality and wasteful methods, and provide solutions for a more positive impact on sustainable development when using disruptive technologies. The paper is organised as follows. Section 2 discusses the materials and methods used in the process and includes the specimen design and the design of experiments approach adopted. In Section 3 and 4 the experimental results are presented and the relationship between process parameters energy consumption, part and scrap weight and production time is analysed. Finally, in Section 5, the main conclusions from the conducted study and recommendations for optimisation of the process are presented.

## 2. Materials and methods

The objectives of this paper are to identify the optimum FDM build parameter settings for part weight and production time and to explore optimisation routes based on balancing this functionality against the economic factors of energy consumption and scrap weight. Using a Design of Experiments (DOE) approach the mechanical properties will be derived via two different types of mechanical test parts. Tensile test part specimens are used to provide values for tensile strength and Young's Modulus, and single edged notched bend (SENB) test parts provide peak SENB load and SENB modulus (Figure 1). For both test part designs the build time, energy consumption used to build the parts and the mean part and scrap weights data will be recorded. The response of each process control factor on the experimental results will be shown, and main effects plots will be used to show the level of influence that each control factor has on each result. From the DOE results the relationships between energy consumption, part weight, scrap weight and production time and energy consumed will be shown and contour plots will be used to identify the following three factor relationships

- Part weight vs scrap weight and energy consumption

- Scrap weight vs part weight and energy consumption
- Energy consumption vs scrap weight and part weight

## 2.1 Build Parameters

To investigate how the build settings affect the process performance, this experimental research was focused on build time, energy consumption, part weight and scrap weight. To acquire the necessary information, the investigated FDM parameters were as follows:

- Slice orientation (SO)
- Number of shells
- Infill %
- Layer height

The SO refers to the orientation at which the layers are printed, and is depicted in Figure 2. For the tensile test part the fused deposition was across the length of the specimen for both builds. Where the SO would be across the width of the specimen was omitted from the experiment as for tensile test specimens the mechanical properties would be limited to the strength of the layer bonding and not the material itself. The Front and Side SO were chosen as in both cases the layer planes are oriented parallel to the loading direction (Figure 2). For the SENB test part, the fused deposition build was across the length of the specimen for one build and across the width for the second build. For simplicity the builds are referred to as the front SO and side SO for both test parts. A shell is a border outline that is printed first for each layer. There is a minimum of one shell per layer (Figure 3 a and 4 a) for this FDM machine (Makerbot Replicator 2). More shells can be added (Figure 3 b and 4 b) resulting in concentric borders being printed towards the centre of the object. If a large number of shells have been chosen and they cannot all fit into the object, the machine will print as many as it can before there is no space left. The width of the shells does not change, regardless of layer height, and remains at 0.4 mm, which is the nozzle diameter. In this research two shell values are considered; 1 and 4. Thus, the printing strategies consider a single outline print and a four outlines print on each layer of the test parts.

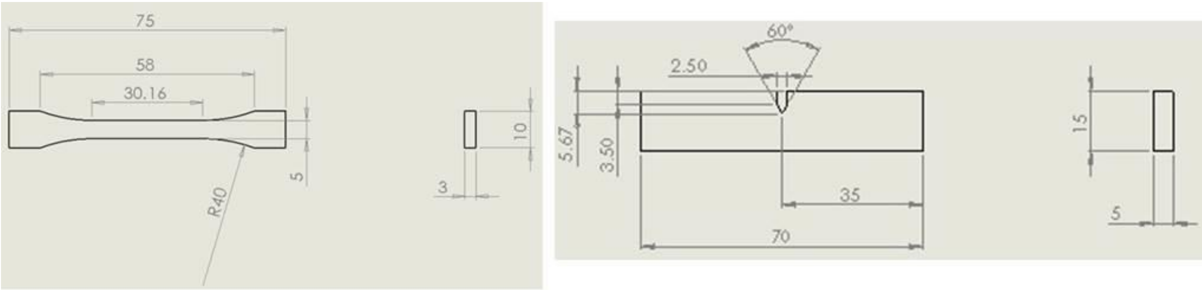
The Infill represents the density of the internal structure of the object. The infill is printed after the shell(s). A 100 % infill (Figure 4) will result in a completely solid structure. An infill that is lower than 100 % will result in a regular hexagonal pattern (Figure 3) being printed, with the hexagons proportionally decreasing in size with a higher infill. A lower infill will reduce the time taken to print, and will reduce the mass of the object. The level of infill is given by a percentage, and the amount can be modified in the design software. This study considers a 100% infill for maximum strength and 60% with reduced material weight and increased build time. In layer based manufacture the object is sliced into layers which are deposited sequentially. The layer height setting defines the thickness of each print layer. A low thickness requires more layers to complete the model which results in an increase in build time, consequently a large thickness layer can improve the time taken to produce the build but can also result in negative quality effects such as the stair step effect on the surface of the part. The layer height can be modified using the design software and in this research a layer height of 0.15 mm and 0.4 mm is considered.

**2.2 Specimen Design**

The focus of this research is optimisation of the properties of FDM Parts. To acquire the necessary information on build time, part weight and material properties the following response variables were determined:

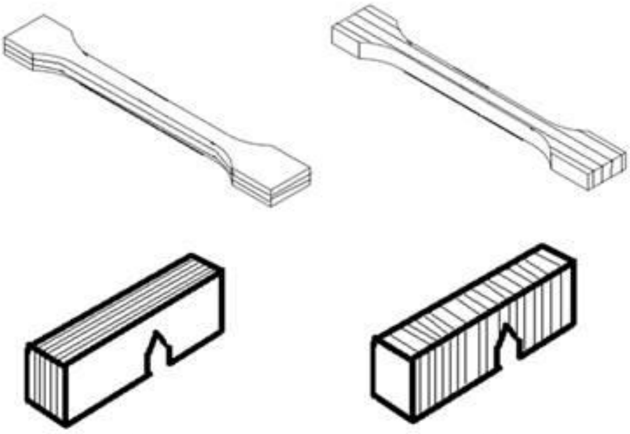
- Scrap Weight
- Part Weight
- Energy consumption
- Production time

Schematics of each are depicted in Figure 1 for a) tensile and b) SENB specimens.
Each design conforms to the appropriate standard; ISO 527-2 (tensile) and ISO 13586 (SENB).



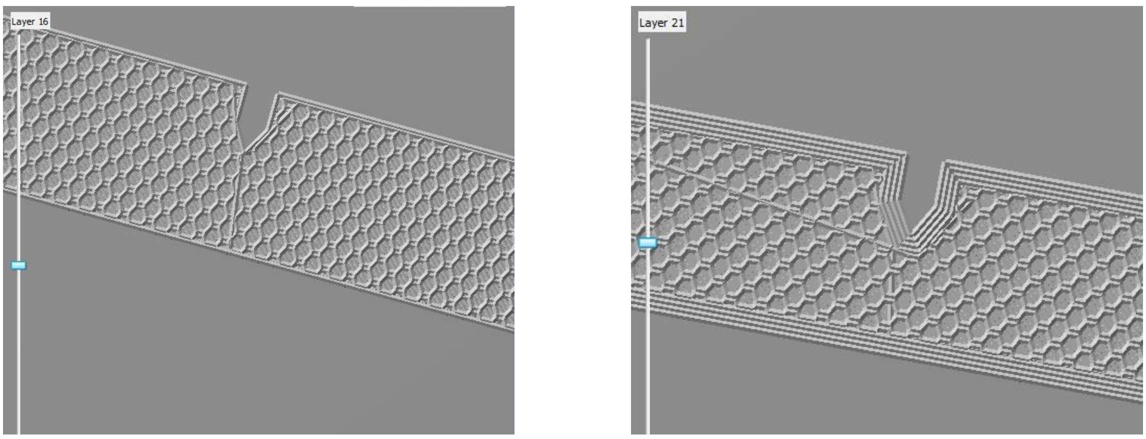

(a) (b)

Figure 1. Specimen schematics of (a) tensile specimen and (b) SENB specimen (all dimensions are in mm, unless otherwise stated).



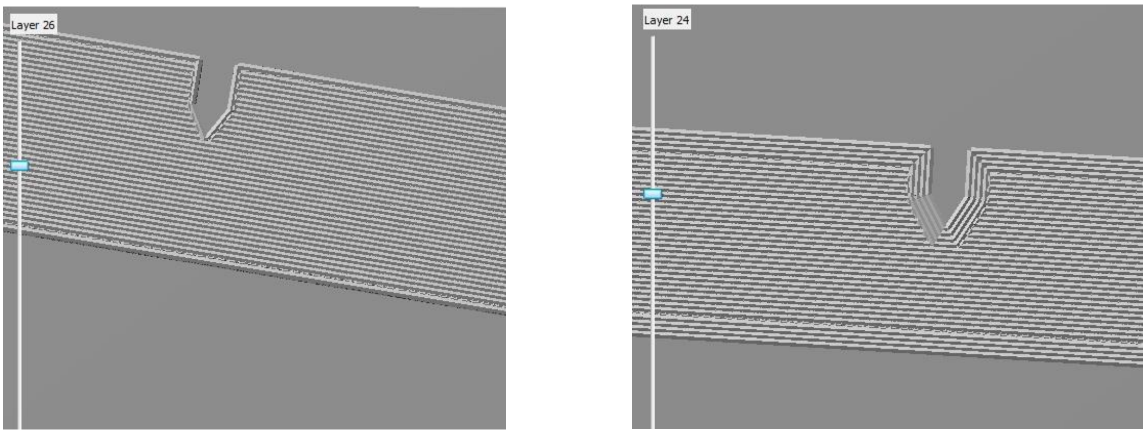
(a) (b)

Figure 2. Representation of the 2 slice orientations (SOs) used in the study (a) Front SO, (b) Side SO.




(a) (b)

Figure 3. SENB test part internal structure for (a) 60 % infill and single shell design (b) 60 % infill and four shell design.




(a) (b)

Figure 4. SENB test part internal structure for (a) 100% infill and single shell design (b) 100% infill and four shell design.

### 2.3 Test material

The material used in this research was polylactic acid (PLA) filament of diameter 1.75 mm, supplied by Makerbot. The filament was designed specifically for use with all fifth generation Makerbot Replicator printers, which includes the Replicator 2 used in this work. PLA is an aliphatic polyester, a biodegradable thermoplastic that can be processed by techniques such as additive manufacturing, injection moulding, extrusion, spinning and casting. PLA products are used in a wide variety of applications; and geometrically complex tools can be additively manufactured. The biodegradability of PLA has led to extensive use in the disposable packaging industry. Sectors where mechanical performance is paramount include the medical implant sector, where quantification of the mechanical properties with the build parameters would be especially important.

### 2.4 Design of Experiments (DOE)

The Taguchi design of experiments (DOE) method was used to plan the research with the objectives of: acquiring data in a controlled way, obtaining information about the behaviour of the FDM process and also identifying significant factors affecting the process. To investigate how the process affects the material performance, this experimental research was focused on the eight outputs defined in section 2.2. The optimisation is based on a function of four process factors, build orientation, infill, the number of shells and layer height. Given that four factors at two levels were considered for the selected material, a Taguchi L16 orthogonal array (OA) was selected (Table 1). A full factorial 2-level DOE was adopted for the study, for both tensile and SENB specimens. The 2-level design incorporating 4 parameters requires $2^4 = 16$ total experiments for each mechanical property to be tested, the sixteen experiments were randomised and each experimental run was repeated. Based on the L16 Orthogonal Array (OA) defined in this way ten trials were performed for each combination of controlled parameters. Thus, 320 experimental trials in total were carried out. The eight response variables are based on the factorial array depicted in Table 1.

Table 1. Full factorial DoE for each of tensile and SENB specimens

| Run | Slice Orientation | Infill (%) | Number of Shells | Layer Height (mm) |
|---|---|---|---|---|
| **1** | Front | 60 | 1 | 0.15 |
| **2** | Front | 60 | 1 | 0.4 |
| **3** | Front | 60 | 4 | 0.15 |
| **4** | Front | 60 | 4 | 0.4 |
| **5** | Front | 100 | 1 | 0.15 |
| **6** | Front | 100 | 1 | 0.4 |
| **7** | Front | 100 | 4 | 0.15 |
| **8** | Front | 100 | 4 | 0.4 |
| **9** | Side | 60 | 1 | 0.15 |
| **10** | Side | 60 | 1 | 0.4 |
| **11** | Side | 60 | 4 | 0.15 |
| **12** | Side | 60 | 4 | 0.4 |
| **13** | Side | 100 | 1 | 0.15 |
| **14** | Side | 100 | 1 | 0.4 |
| **15** | Side | 100 | 4 | 0.15 |
| **16** | Side | 100 | 4 | 0.4 |

**2.5 FDM**

All the specimens were sliced and prepared for printing using MakerWare software, and then printed using Makerbot Replicator 2 printers, using PLA filament of 1.75 mm diameter. The Makerbot Replicator 2 translates the CAD file instructions via USB or SD card, heats the filament and servo motors drive it through the nozzle to perform the layer manufacture. The machine has a build volume of 285 x 153 x 155 mm and a layer resolution of up to 100 µm. It is limited to processing PLA filaments of 1.75 mm diameter and has a nozzle diameter of 0.4 mm. Default settings for the extrusion temperature and extrusion speed of the Makerbot were employed as recommended by the manufacturer.

## 2.6 Data Analysis

The data for weight was measured using laboratory scales, and the times were measured with a stopwatch. The power usage was measured using an Energenie Power Meter with a +/- 2% accuracy for power measurements. The test results was analysed using MiniTab 16. Main effects plots for the means (of each measured property from each Run of 10 specimens) were generated to assess the effect of each of level of a parameter (positive or negative, depending on the gradient) on a given property. Pareto and contour plots were generated to determine parameter interactions and three way interactions.

## 3. Results

This section describes the results obtained from collation of data from the measured response outputs, and quantifies their value(s) according to the machine build parameter inputs.

## 3.1 Scrap Weight

The design of experimental results for the manufacture of both SENB and tensile test parts show that scrap weight reduces dramatically (83.3 % and 24.5 % respectively) with a change in SO (Table 2). This is due to the reduction in contact area between the part and the build plate, hence determining the size of the raft and it is therefore expected that this is the most important factor contributing to scrap. It is clear from Figure 5 and 6 that the side SO reduces the scrap weight. A pareto analysis to identify significant interactions shows that there are none for the SENB parts. The same can be said for the Tensile test parts however some interactions are more important than single factors (with the exception of SO), with the interaction of SO and number of shells being the highest influence on the amount of scrap, despite the number of shells being inconsequential as a single factor.

To minimise scrap weight, the SO selection should be one where the part and build plate contact area is reduced. This becomes useful for reducing the scrap produced, saving money on material costs and waste disposal. A smart selection of SO in terms of surface area can also facilitate the removal of the raft and part from the build plate. However, when selecting SO, it must be considered whether supports will be needed, as this could increase the scrap produced.

Table 2. Response for mean scrap weight

| SENB part scrap weight response | | | | |
|---|---|---|---|---|
| Factor | SO | Infill | Number of shells | Layer height |
| Level 1 [g] | 2.16 | 1.22 | 1.28 | 1.22 |
| Level 2 [g] | 0.3575 | 1.2911 | 1.2361 | 1.2950 |
| Rank importance | **1** | 3 | 4 | 2 |
| Influence [g] | 1.80 | 0.062 | 0.047 | 0.07 |
| Influence [%] | **83.3** | 5.0 | 3.6 | 5.7 |
| Tensile part scrap weight response | | | | |
| Level 1 [g] | 1.55 | 1.37 | 1.31 | 1.42 |
| Level 2 [g] | 1.17 | 1.35 | 1.41 | 1.30 |
| Rank importance | **1** | 4 | 3 | 2 |
| Influence [g] | 0.38 | 0.018 | 0.098 | 0.12 |
| Influence [%] | **24.5** | 1.3 | 7.4 | 8.4 |

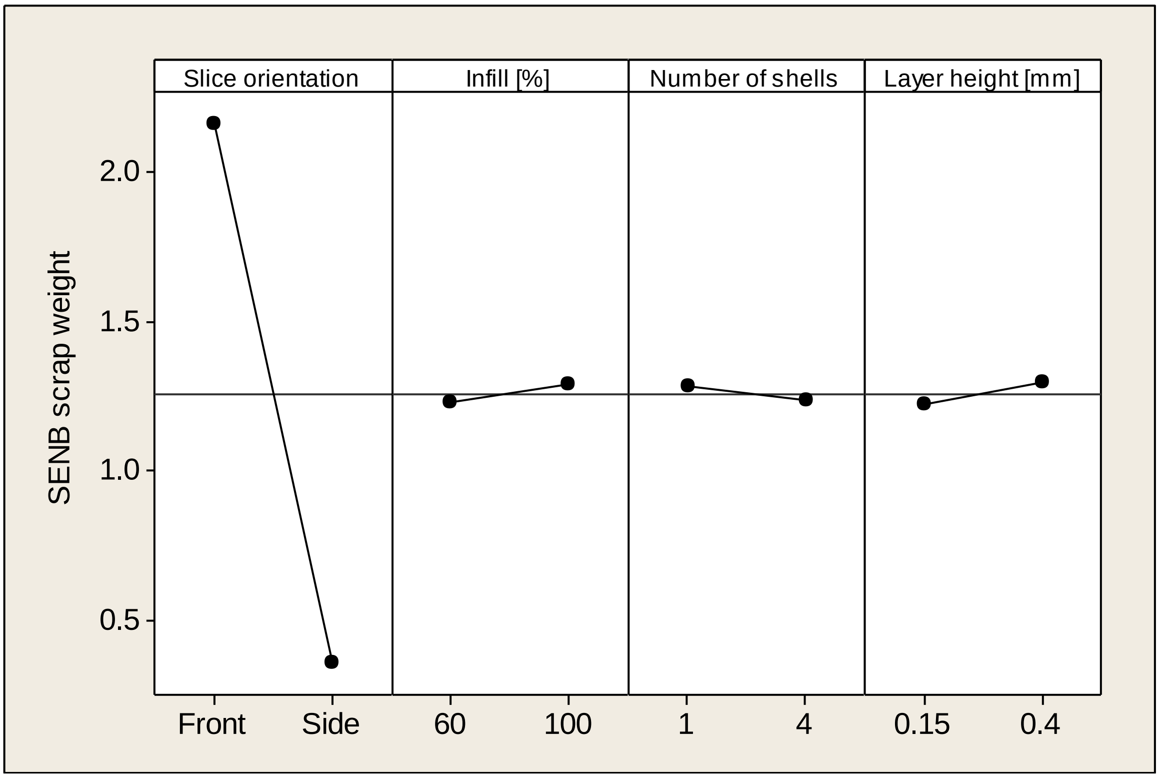



Figure 5. Main effects plot for SENB specimen scrap weight.

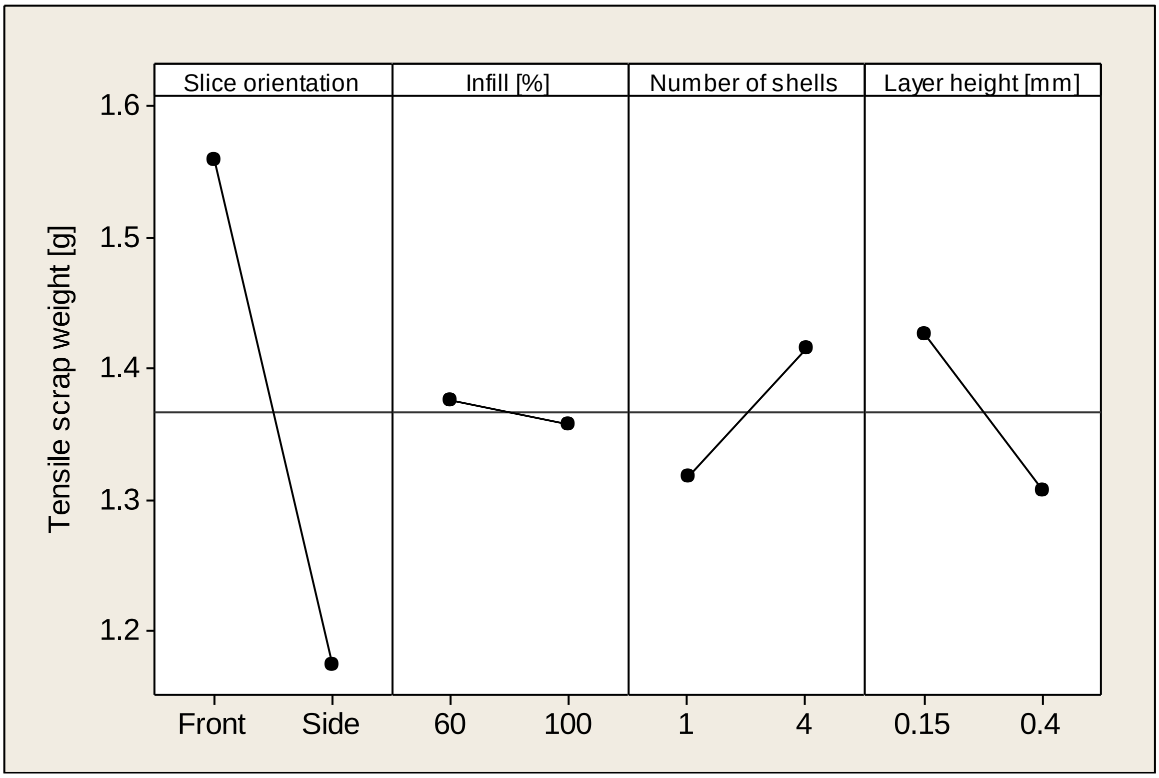



Figure 6. Main effects plot for tensile specimen scrap weight.

**3.2 Part Weight**

Infill followed by the number of shells are the dominant factors that influence part weight for both the SENB and tensile test parts (Table 3). For both it can be seen that an increase in infill and the number of shells results in a heavier part (Figure 7 and 8). Therefore, when producing parts where reduced part weight is the dominant requirement over mechanical strength, a reduction of infill and the number of shells will minimise part weight. The reduction in infill is 29.8 % for the SENB test part compared to a 13.9 % reduction for the tensile specimens. A pareto analysis for the SENB test parts shows that infill and the number of shells are significant, but there are a number of interactions that are significant. In particular the 2 way interactions of infill and number of shells and SO and number of shells, and the three way interaction of SO, infill and number of shells. The pareto analysis to identify significant interactions for the tensile test parts shows no significant interaction, but there are interactions that are higher in influence to the single factors of SO and layer height.

Table 3. Response for mean part weight

| SENB Part weight response | | | | |
|---|---|---|---|---|
| Factor | SO | Infill | Number of shells | Layer height |
| Level 1 [g] | 5.74 | 5.09 | 5.57 | 5.89 |
| Level 2 [g] | 5.97 | 6.62 | 6.14 | 5.81 |
| Rank importance | 3 | **1** | 2 | 4 |
| Influence [g] | 0.22 | 1.52 | 0.57 | 0.08 |
| Influence [%] | 3.8 | **29.8** | 10.2 | 1.3 |
| Tensile Part weight response | | | | |
| Level 1 [g] | 1.91 | 1.79 | 1.85 | 1.89 |
| Level 2 [g] | 0.929 | 2.04 | 1.99 | 1.94 |
| Rank importance | 4 | **1** | 2 | 3 |
| Influence [g] | 0.014 | 0.25 | 0.14 | 0.046 |
| Influence [%] | 0.7 | **14.0** | 7.5 | 2.4 |

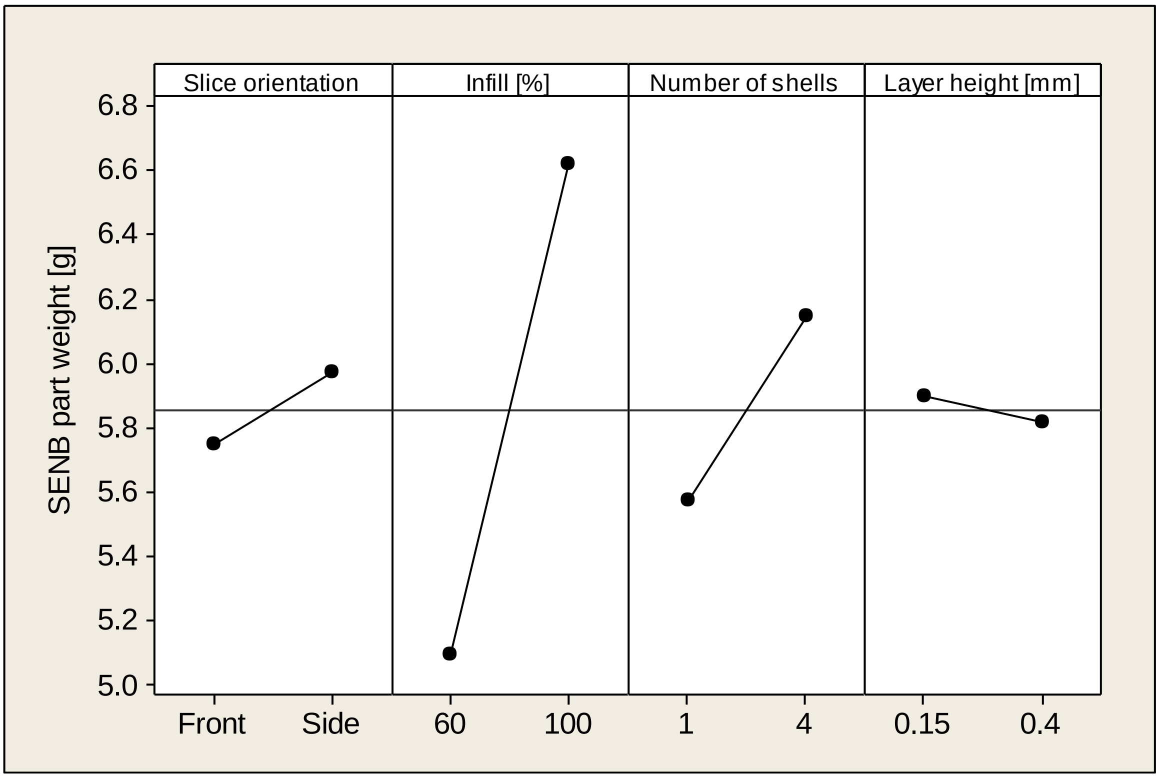



Figure 7. Main effects plot for SENB specimen part weight.

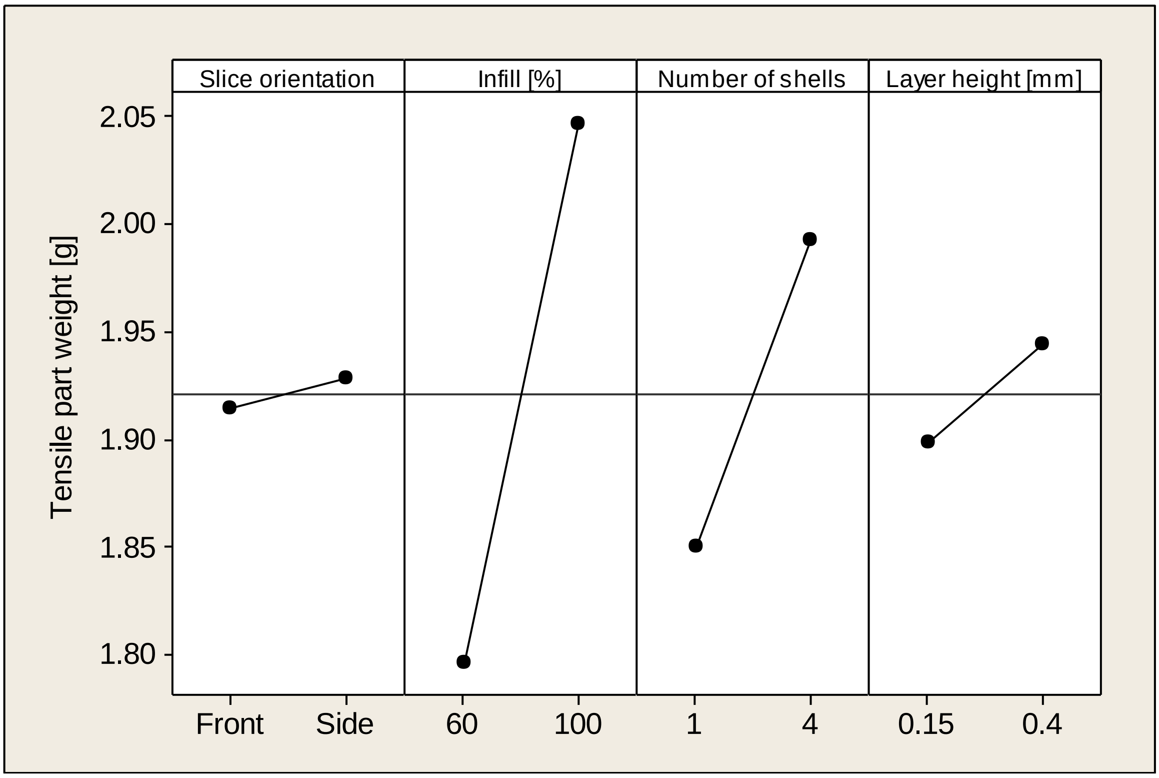



Figure 8. Main effects plot for tensile specimen part weight.

**3.3 Energy consumption**

For SENB specimens, the layer height was the most significant parameter affecting energy consumption (influence of 57.6 %) followed by the SO (Table 4). The interaction between these parameters was also significant, as was the interaction between SO and infill. A higher layer height reduces the build time (as the time required to reach specified thickness is reduced) and hence the energy consumption. The influence of SO is less obvious, although the findings seem to indicate that it is more efficient to build fewer layers of longer length (front SO Figure 2) than more layers of shorter length (side SO Figure 2). With a side SO, the machine makes more directional changes. The relative importance of each parameter is illustrated in the main effects plot (Figure 9), which shows that the infill level and no. of shells have little influence (Pareto analysis confirmed these parameters were insignificant at 95 % confidence level). It is reasonable to assume however, that a lower infill level and lower number of shells would reduce energy consumption, and it is therefore possible that the slight gradients in Figure 9 are indicative of recommending these lower levels for infill and no. of shells. However the significance of this could only be confirmed by measuring their effects in isolation i.e.

keeping SO and layer height constant. Where all build parameters are assessed however, the layer height followed by the SO are the only significant ones, and to reduce energy consumption in SENB specimens a front SO and 0.4 mm layer height are recommended.

For tensile specimens, the only significant parameter affecting energy consumption (at 95 % confidence level) was layer height with an influence of 48.5 % (Table 4), which as with the SENB specimens, is optimised with the higher value and for the same reasons. In contrast, the SO is insignificant for the tensile specimens, and this is due to the layers being sliced along the length of the sample in both cases (Figure 2). There were no significant interactions. As with the SENB specimens, it is possible that the infill and number of shells have an influence, but this is too small to be detected due to the dominance on the energy consumption by the layer height.

Table 4. Response for energy consumption

| Energy consumption for producing SENB test parts | | | | |
|---|---|---|---|---|
| Factor | SO | Infill | Number of shells | Layer height |
| Level 1 [kWh] | 0.02181 | 0.02332 | 0.02330 | 0.03299 |
| Level 2 [kWh] | 0.02514 | 0.02363 | 0.02365 | 0.01396 |
| Rank importance | 2 | 4 | 3 | **1** |
| Influence [kWh] | 0.00332 | 0.00030 | 0.00035 | 0.01902 |
| Influence [%] | 15.2 | 1.2 | 1.5 | **57.6** |
| Energy consumption for producing tensile test parts | | | | |
| Level 1 [kWh] | 0.009613 | 0.009463 | 0.010225 | 0.012700 |
| Level 2 [kWh] | 0.009625 | 0.009775 | 0.009013 | 0.006538 |
| Rank importance | 4 | 3 | 2 | **1** |
| Influence [kWh] | 0.000013 | 0.000313 | 0.001213 | 0.006163 |
| Influence [%] | 0.1 | 3.3 | 11.8 | **48.5** |

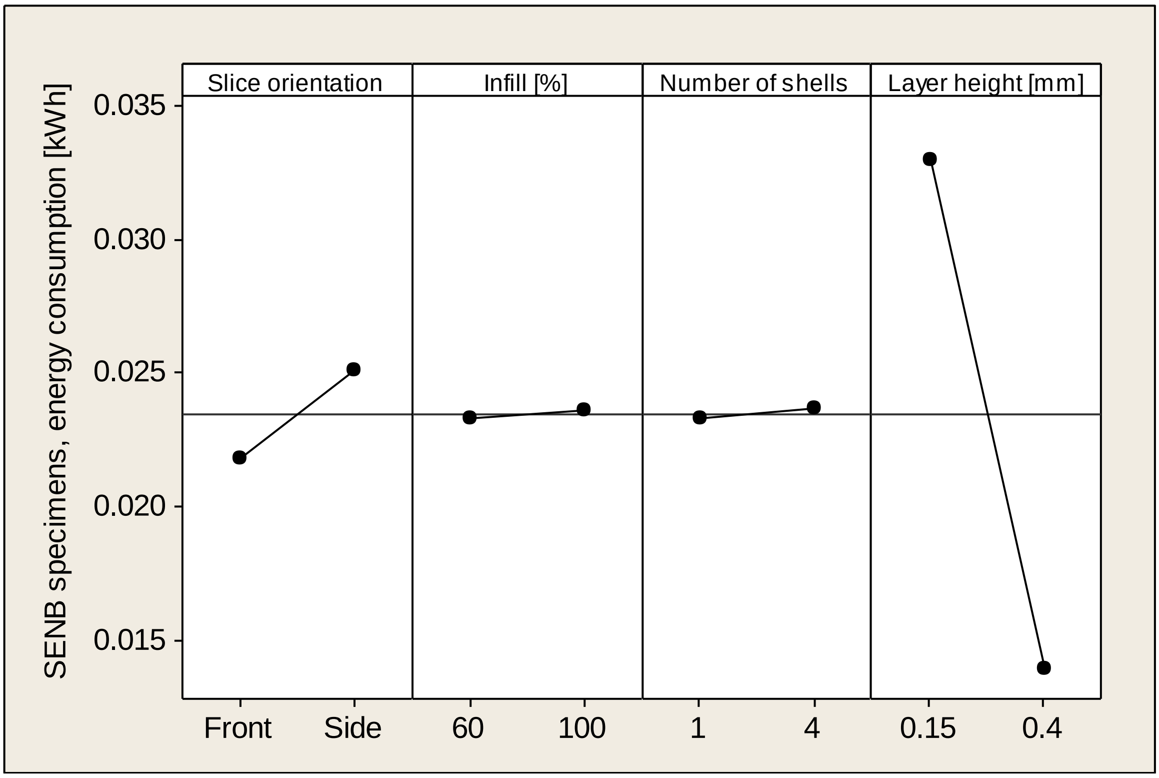



Figure 9. Main effects plot for energy consumption in production of SENB specimens.

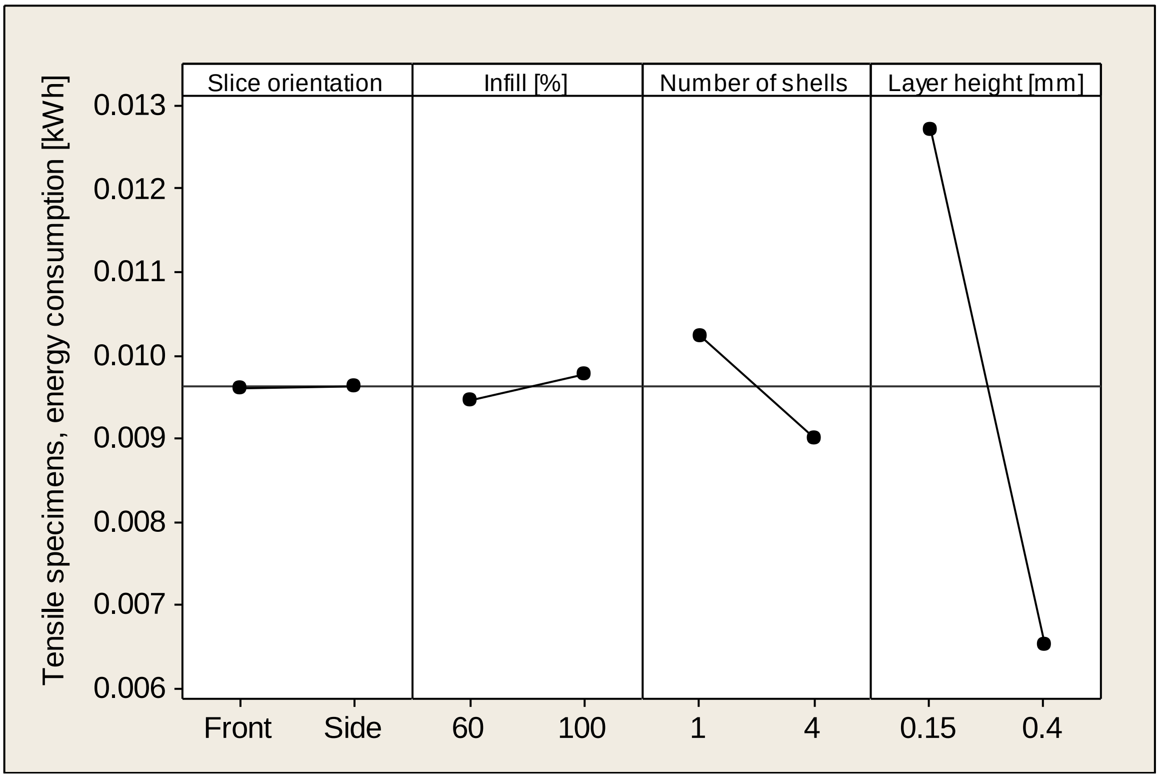



Figure 10. Main effects plot for energy consumption in production of tensile specimens.

### 3.4 Production time

Layer heigh is the most important influence on time when producing SENB parts followed by SO, lower layer height and side SO results in an increase of time of 57 % and 56 % respectively (Table 5). An increase in the amount of layers is shown to require more power (Figure 10) and it is clear that the reduction in the amount of layers has a significant influence on the time to produce a part (Figure 11). Both infill and the number of shells have very little influence on the producution time. Interactions and the lowest and highest settings. A pareto analysis to identify significant interactions confirms that layer height and SO are significant for the production of SENB parts, it also shows that the 2 way interaction of SO and layer height is significant.

The tensile test parts are similar to the SENB parts in that the layer height is the most critical factor when considering production time (Table 5). A decrease in the layer height results in a decrease in build time by around 45 % (Figure 12). A parato analysis confirms layer height as significant and that no interactions are significant. The 2 way interaction of SO and number of shells is as significant as the single factor of number of shells and is more significant than the single factors of SO and Infill.

Table 5. Response for mean production time

| SENB part production time | | | | |
|---|---|---|---|---|
| Factor | So | Infill | Number of shells | Layer height |
| Level 1 [mins] | 21.63 | 27.88 | 27.25 | 38.75 |
| Level 2 [mins] | 33.75 | 27.5 | 28.13 | 16.63 |
| Rank importance | 2 | 4 | 3 | **1** |
| Influence [mins] | 12.13 | 0.38 | 0.88 | 22.13 |
| Influence [%] | 56.0 | 1.3 | 3.2 | **57.1** |
| Tensile part production time | | | | |
| Level 1 [mins] | 10.25 | 10.5 | 11.25 | 13.87 |
| Level 2 [mins] | 11.12 | 10.87 | 10.12 | 7.50 |
| Rank importance | 3 | 4 | 2 | **1** |
| Influence [mins] | 0.87 | 0.37 | 1.12 | 6.37 |
| Influence [%] | 8.4 | 3.5 | 10.0 | **46.0** |

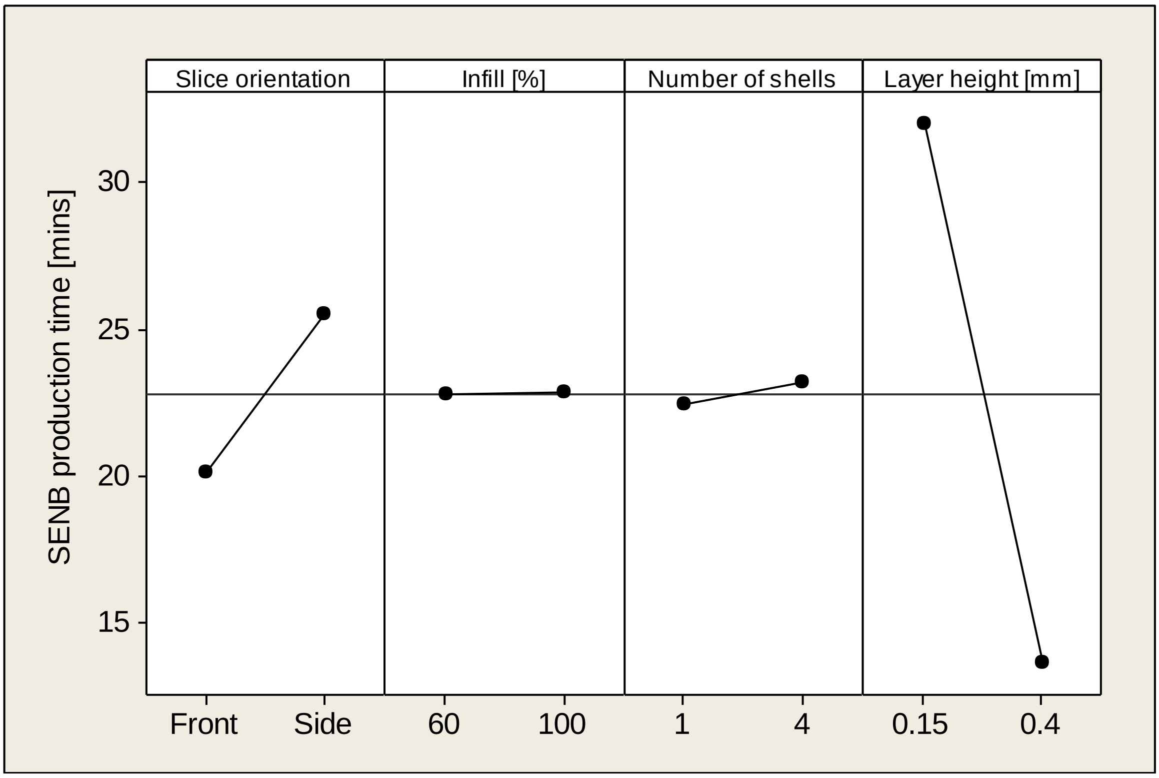



Figure 11. Main effects plot for production time of SENB specimens.

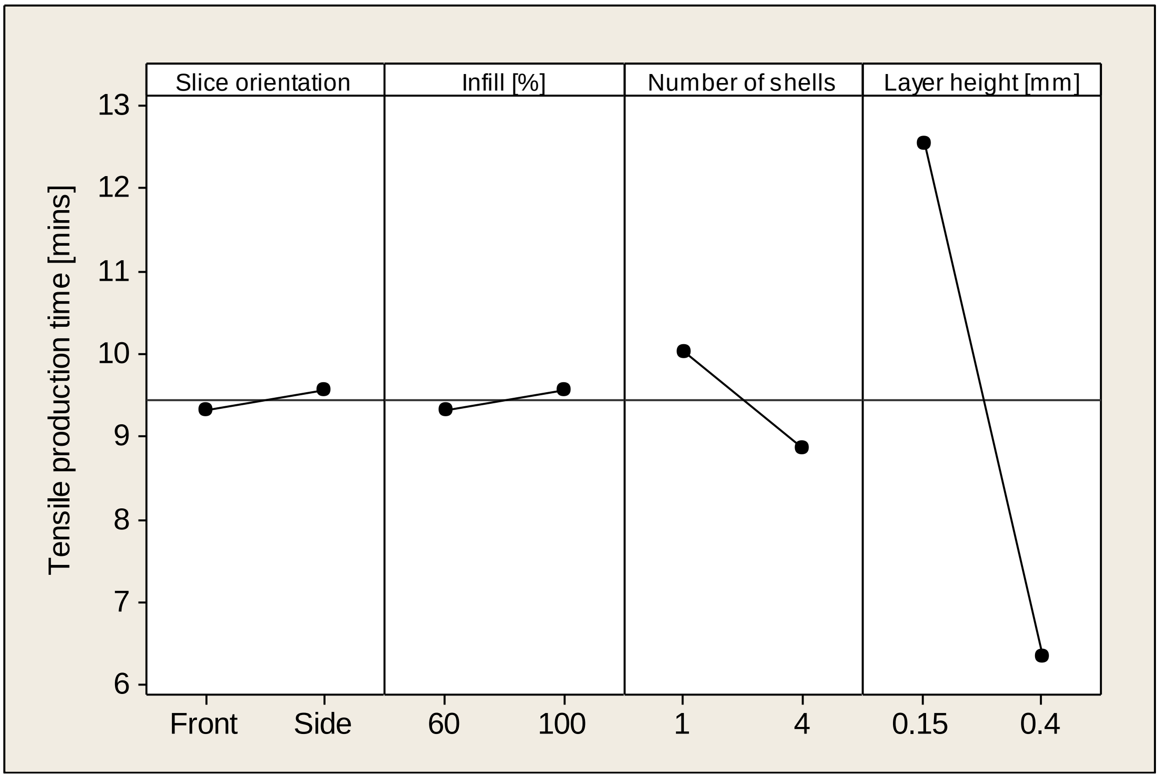



Figure 12. Main effects plot for production time of tensile specimens.

### 3.5 Energy consumption and part and scrap weight

For SENB specimens, optimisation with respect to lower material usage and energy consumption is achieved with the build parameters of Run 10 (Table 1). Analysis of these parameters aids the decision making process for cost reduction, which is especially important in rapid prototyping. Figure 13 further highlights the importance of the SO to scrap weight with the side SO provide the lowest weight, and of the lower layer height provides the lowest energy consumption.

For tensile specimens, a similar trend for part weight to the SENB specimens is observed (Figure 14). This is to be expected as only the dimensions differ. However whereas the scrap weight of SENB specimens was mostly dependent on SO, there is a more complex relationship for tensile patterns, with Run 14 in addition to Run 10 yielding very low scrap weight. Still, in combination with both part weight and energy consumption, Run 10 appears the optimum for efficiency. However Runs 12 and 16 both consumed less energy than Run 10. This highlights how multi-objective optimisation depends on the relative importance of the outputs to each other where one particular set of parameters (e.g. Run 10 for SENB specimens) is not the optimum for each output.

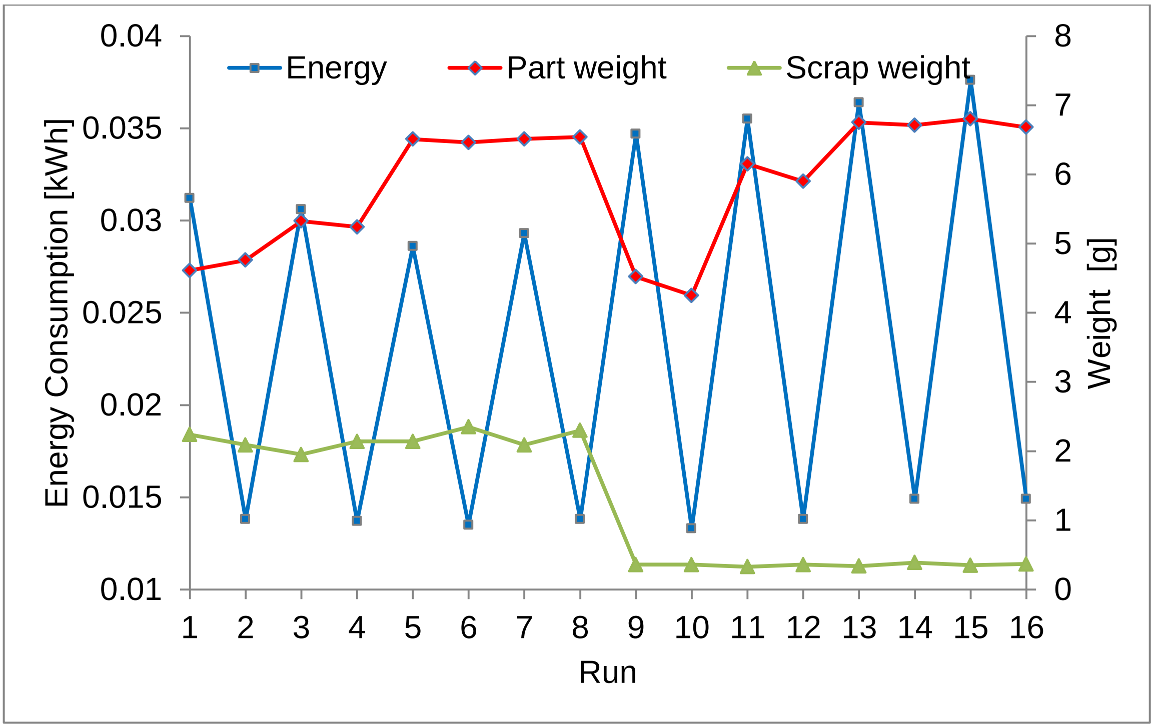



Figure 13. Energy consumption, part weight and scrap weight of SENB specimens.

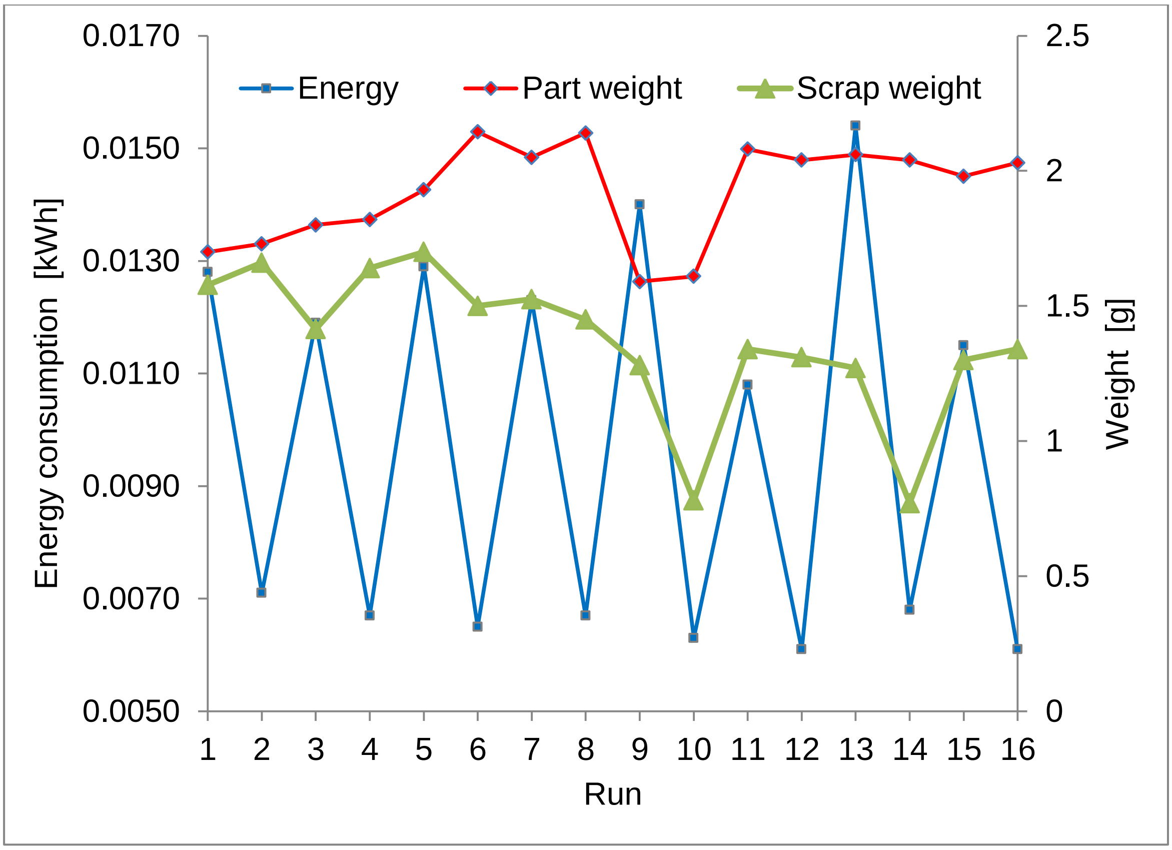



Figure 14. Energy consumption, part weight and scrap weight of tensile specimens.

### 3.6 Production time and part and scrap weight

For the production of the SENB parts it can be seen that the production time averages are lower for experiments 1 to 8 and higher for 9-14, the inverse is true for scrap weight (Figure 15). For SENB parts layer height is the most important factor that affects production time (Figure 11), and SO is the most import and factor for scrap weight and infill is important for part weight (Figure 5 and 7 respectively). The increase and decrease on the production time due to layer height have no direct influence on the part weight. One would assume that increased part weight due to an increase in the volume of polymer deposited and fused would require more deposition time but this result shows that this is not the case.

For the production of the tensile test parts layer height is the factor that has the most influence on production time, with a smaller height resulting in increased time (Figure 12). SO is the most important factor that affects scrap weight for tensile parts and infill is important for part weight (Figure 6 and 8). There is no direct correlation between production time and part weight but for scrap weight there is a correlation in six experiments (9,10,11,13,14 and 15). The scrap weight does correlate to production time but this is not the case in experiments 12 and 16. In these experiments there are a higher number of shells and a larger layer height. This two way interaction is not significant but it is the third highest influence on the scrap weight.

It can be seen in Figure 15 and 16 that parts can be made quickly, with minimal scrap, which is a crucial trade-off, particularly for small companies who have to race to get products to market. A product can be made quickly, but wastage must be minimised. Every run with a large layer height will give a lower print time, and every run with a Side SO will give a low scrap weight. So for the production of SENB parts 10, 12, 14 and 16 are optimum experiments. For tensile parts no correlation can be observed for the first eight experiments. 9 to 16 provide some possibility for optimisation. However, experiments 12 and 16 show that combining the two blindly does not give optimal results. It is apparent that the settings in experiment 13 are a poor option, given the longest amount of time to print, despite its Side SO. It is also clear that the experiment 10 and 14 provide optimal combinations. Although they don’t give the lowest time taken, they give the lowest scrap weight, and have relatively low print times, due to their larger layer height.

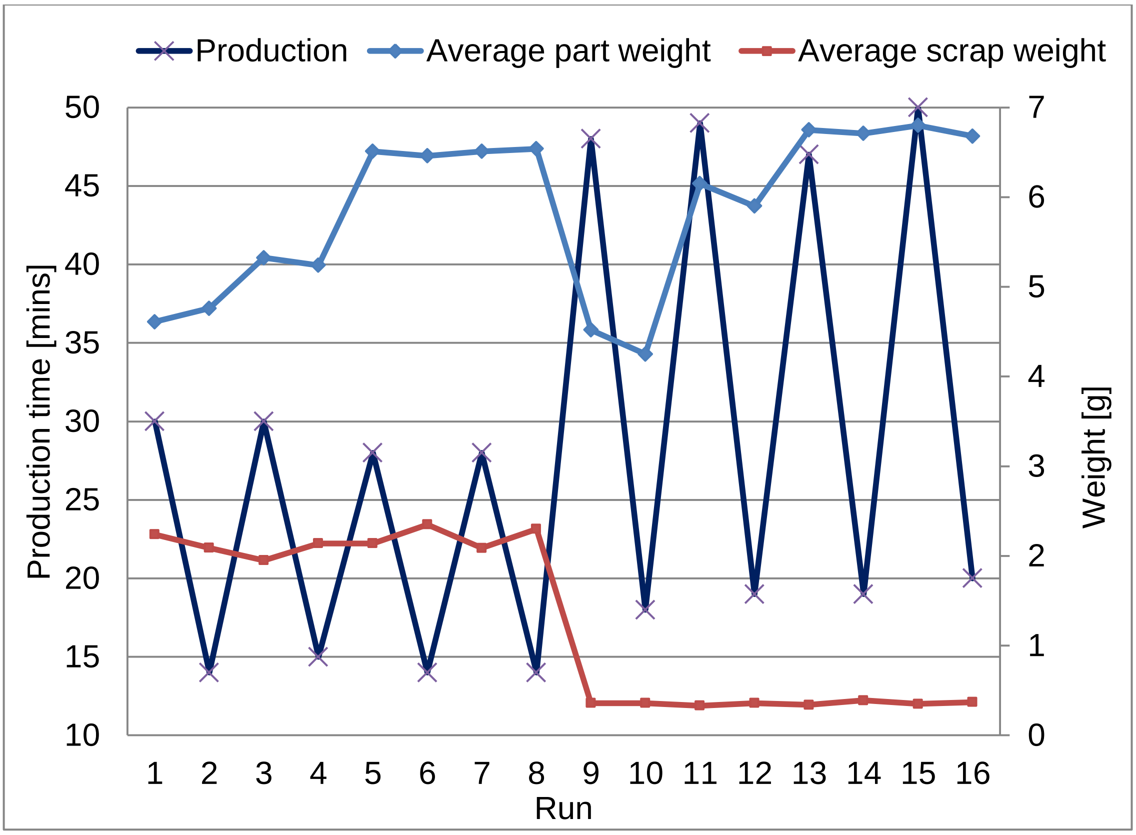



Figure 15. Production time, part weight and scrap weight of SENB specimens.

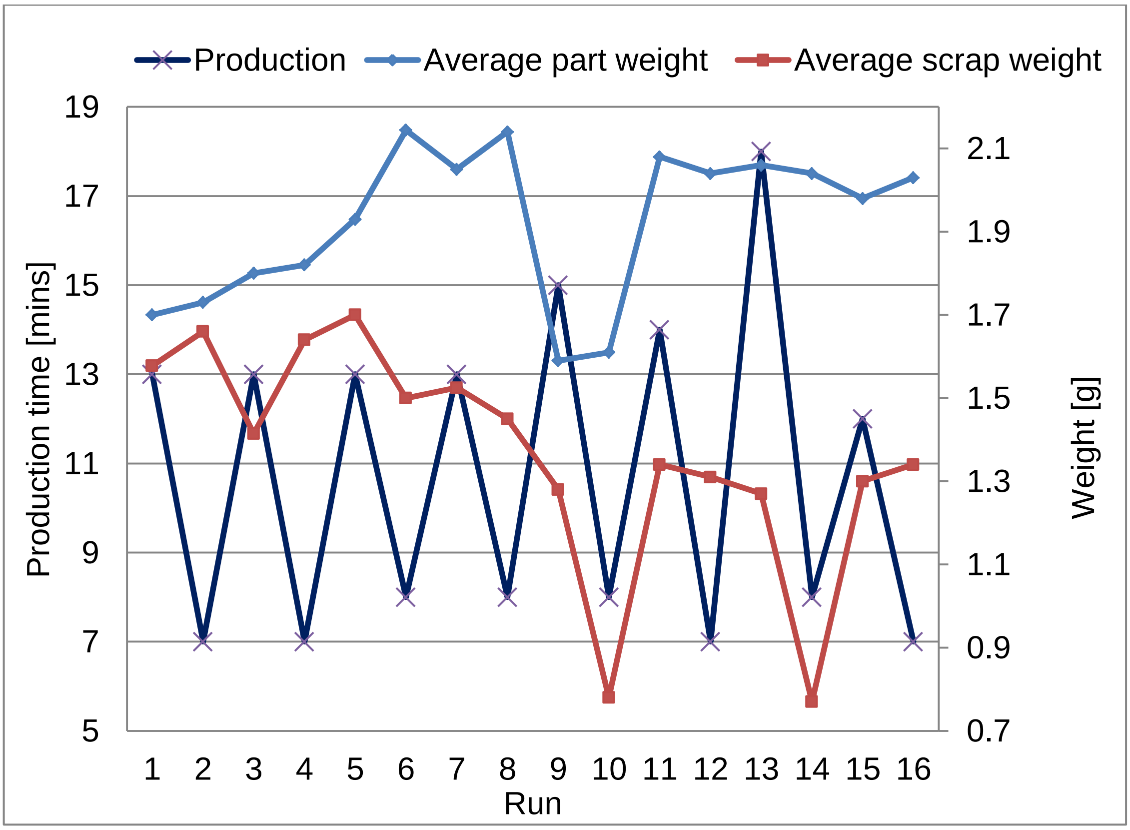



Figure 16. Production time, part weight and scrap weight of tensile specimens.

### 3.7 Production time and energy consumed

For the SENB and tensile test part it can be seen that when considering the production time and the amount of energy consumed it's clear that there is a correlation. It can be observed in Figure 17 and 18 that eight of the runs result in higher energy consumption and a higher production time than the remaining eight. The Full factorial DoE for each of tensile and SENB specimens (Table 1) shows that layer height is the control factor that influences this change in effect. The responses for mean energy consumption and production time (Table 4 and 5 respectively) both confirm that the layer height is ranked as the most important factor. It can be seen that for both responses and both test parts (Figure 9-12) that the low height gives a results in higher production time and energy consumption. The result shows that to meet the target z axis destination there is an energy and time requirement, and by reducing the layer height from 0.4 mm to 0.14 there is an increase in the work from the x and y coordinate cycles.

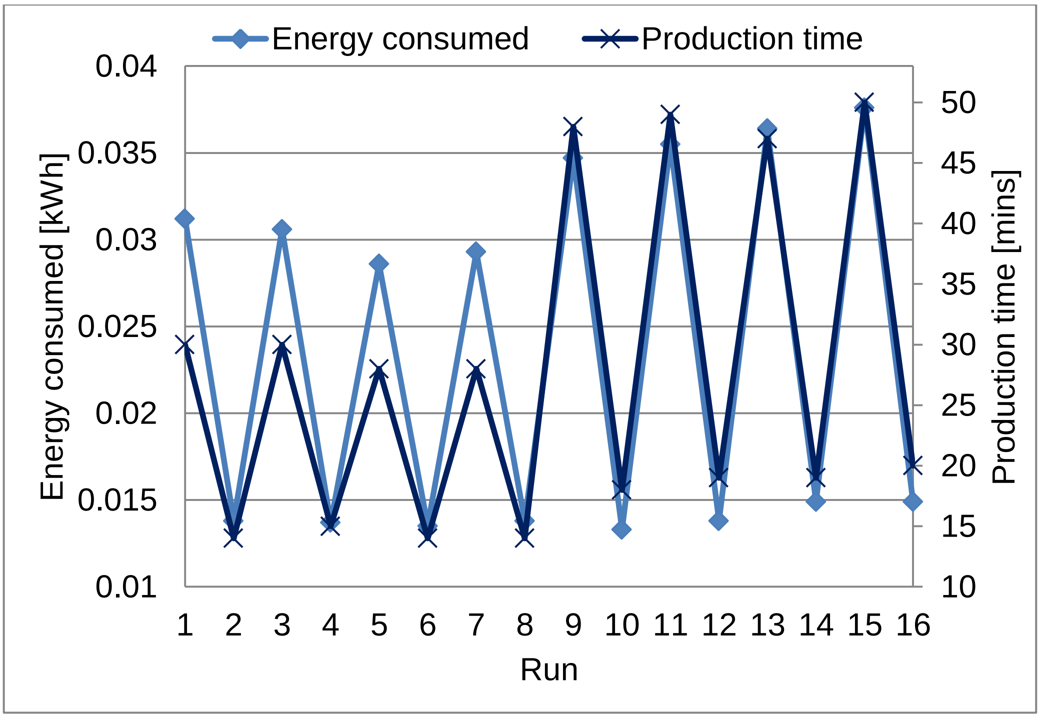



Figure 17. Energy consumption and production time of SENB specimens.

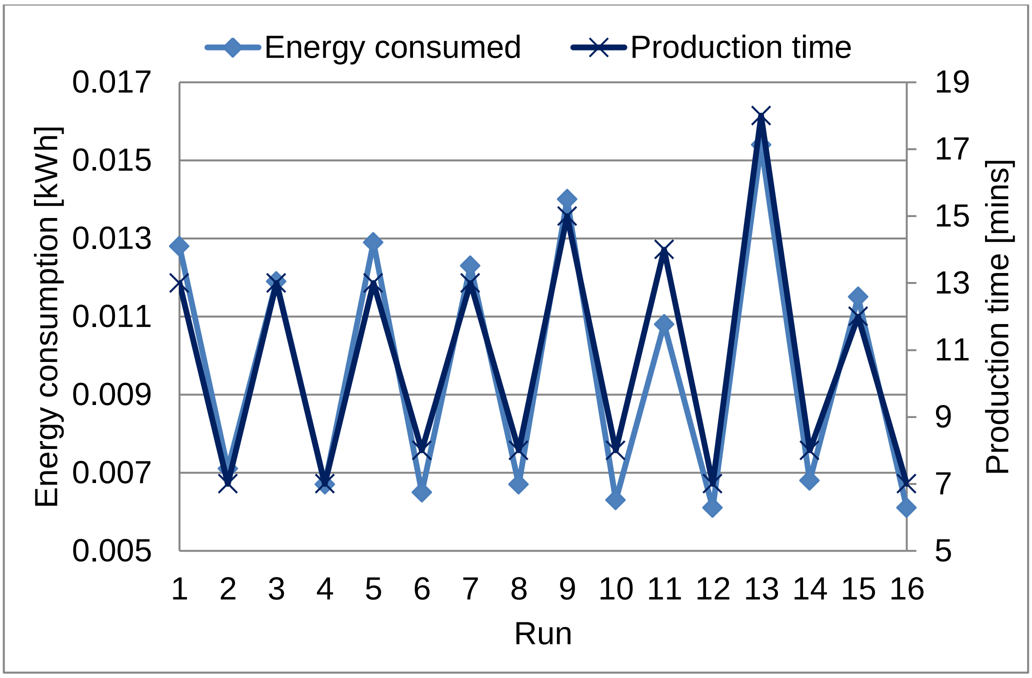



Figure 18. Energy consumption and production time of tensile specimens.

## 4. Contour plots

Based on the experimental results, contour plots were used to explore the relationship between three variables. The plots are used to assess the contribution of the processing parameters in two dimensions, with x- and y-factors plotted and response values represented by colour.

### 4.1 Three factor relationship for SENB test parts

Figure 19 shows that when optimising for energy consumption and part and scrap weight there is an optimal zone (labelled 1) where each is minimised. This zone is very small, as optimisation is only possible when using the build parameters of Experiment 10 (Fig 13). Figure 19 highlights the importance of build parameter optimisation for processing efficiency, with the presence of an inefficient, sub-optimal zone (labelled 3), as well as zones where two factors can be optimised whilst compromising on the third (labelled 2) show that efficiency savings can be missed. These three factors can be optimised co-operatively for maximum efficiency. This is confirmed by Figure 20 and 21, where the response was changed to scrap weight and energy consumption respectively. In both Figures the optimal zone is labelled '1'.

The contour plot investigating three factors together with a focus on the build time when producing SENB parts (Figure 22) shows that as energy consumption increases so does the build time. This phenomenon increases across the full part weight range up till 0.032 kWh.  Above this consumption level the part weight is influential, and the highest build times (>350 mins) can be seen at the highest energy consumption level and the highest part weight.

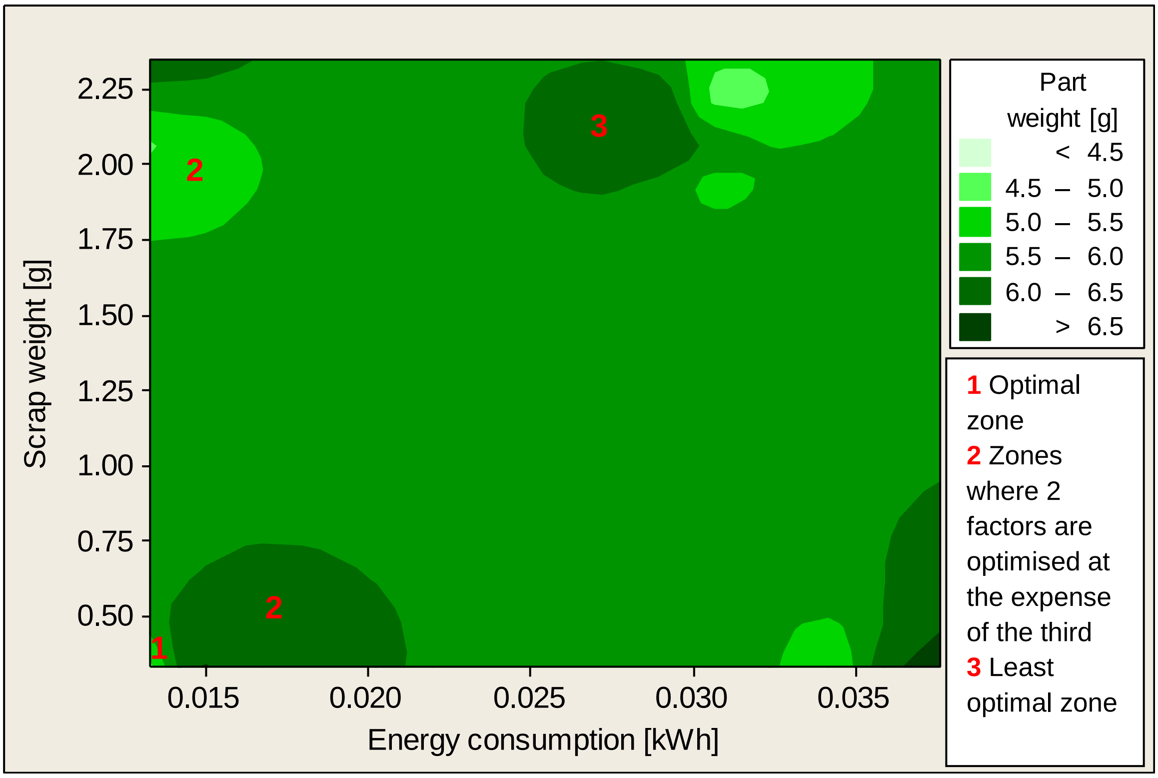



Figure 19. Contour plot of part weight vs scrap weight and energy consumption for SENB specimens.

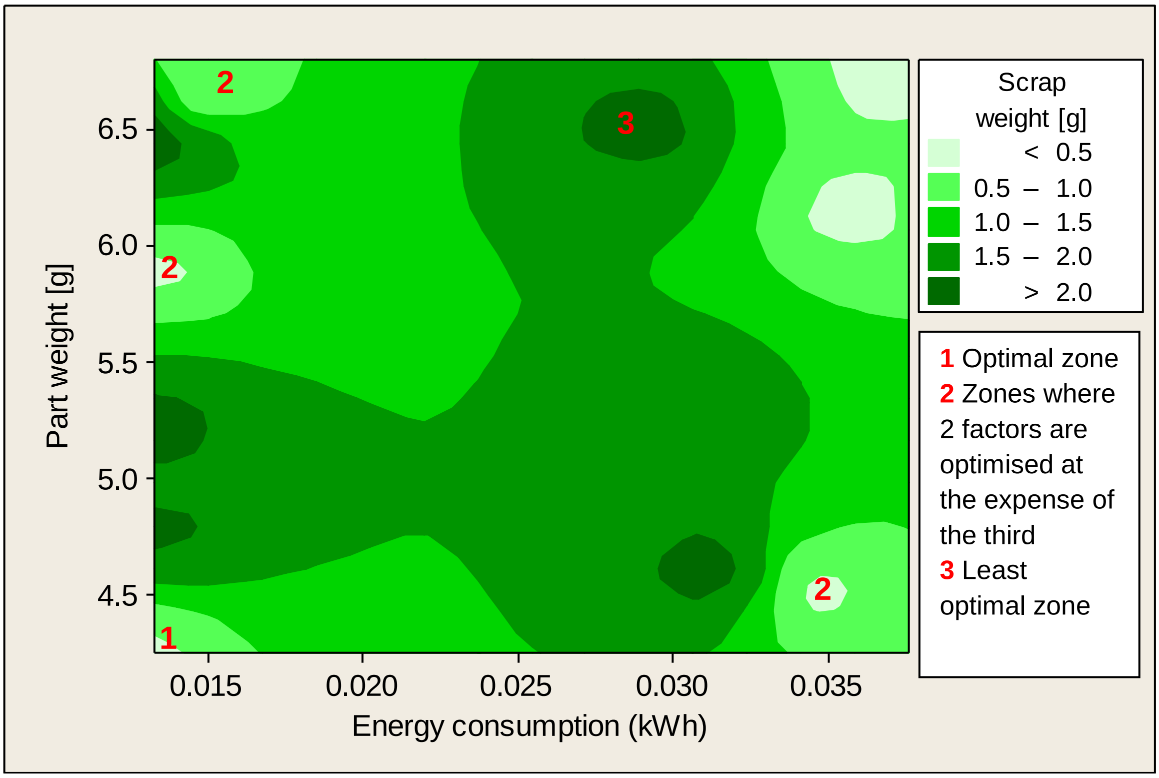


Figure 20. Contour plot of scrap weight vs part weight and energy consumption for SENB specimens.

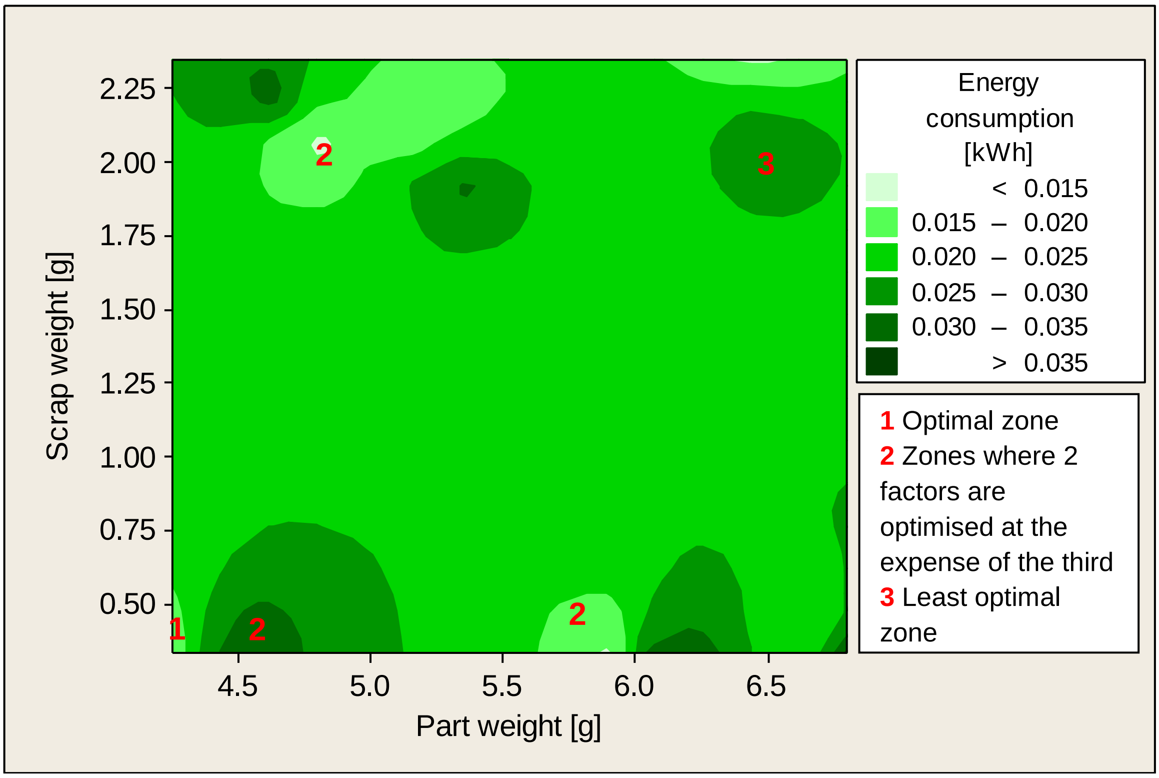



Figure 21. Contour plot of energy consumption vs scrap weight and part weight for SENB specimens.

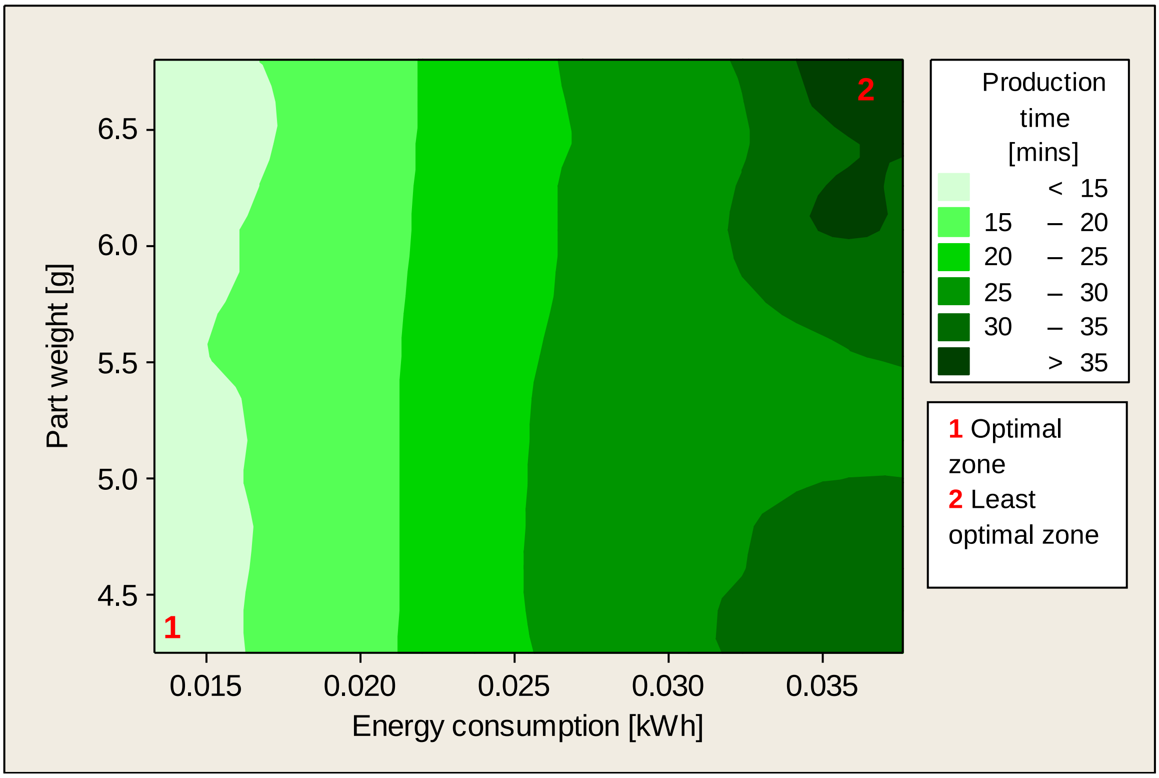



Figure 22. Contour plot of production time vs part weight and energy consumption for SENB specimens.

### 4.2 Three factor relationship for tensile test parts

The contour plot investigating three factors together with a focus on tensile scrap weight (Figure 23) shows that there are three small regions of high scrap weight, one of which stands alone with an intermediate level of energy consumption and part weight. The plot shows that there are also two low scrap weight regions the lowest of which is at the lowest part weight and the lowest level of energy consumption (labelled 1). Therefore as with the SENB specimens cooperative optimisation of these three factors can be achieved. The optimal zone is also highlighted in Figure 24 (focus on energy consumption) and Figure 25 (focus on part weight).

The contour plot investigating three factors together with a focus on the build time of the tensile test parts (Figure 26) shows that build time results in an increase in the energy consumption. This result is independent of the part weight until reaching energy consumption of 0.012 kWh. Above this energy consumption two distinct high build times emerge, the highest of which is at the highest energy consumption and highest part weight regions.

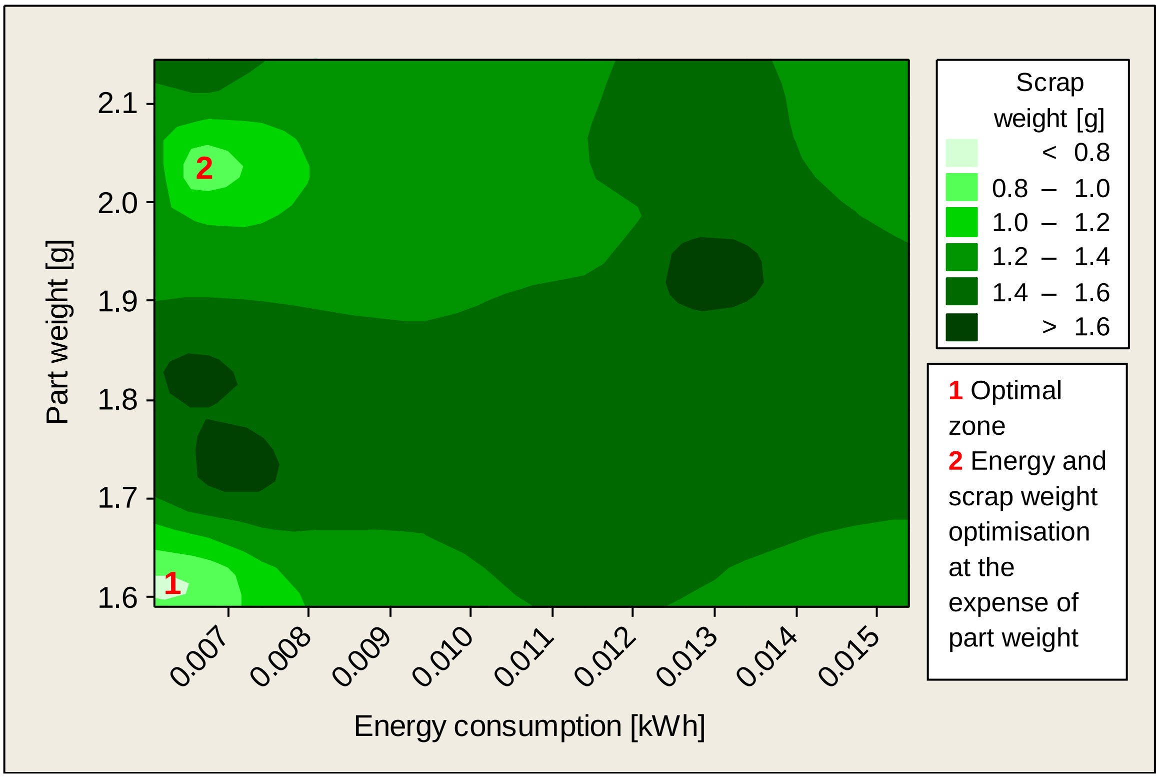



Figure 23. Contour plot of scrap weight vs part weight and energy consumption for tensile specimens.

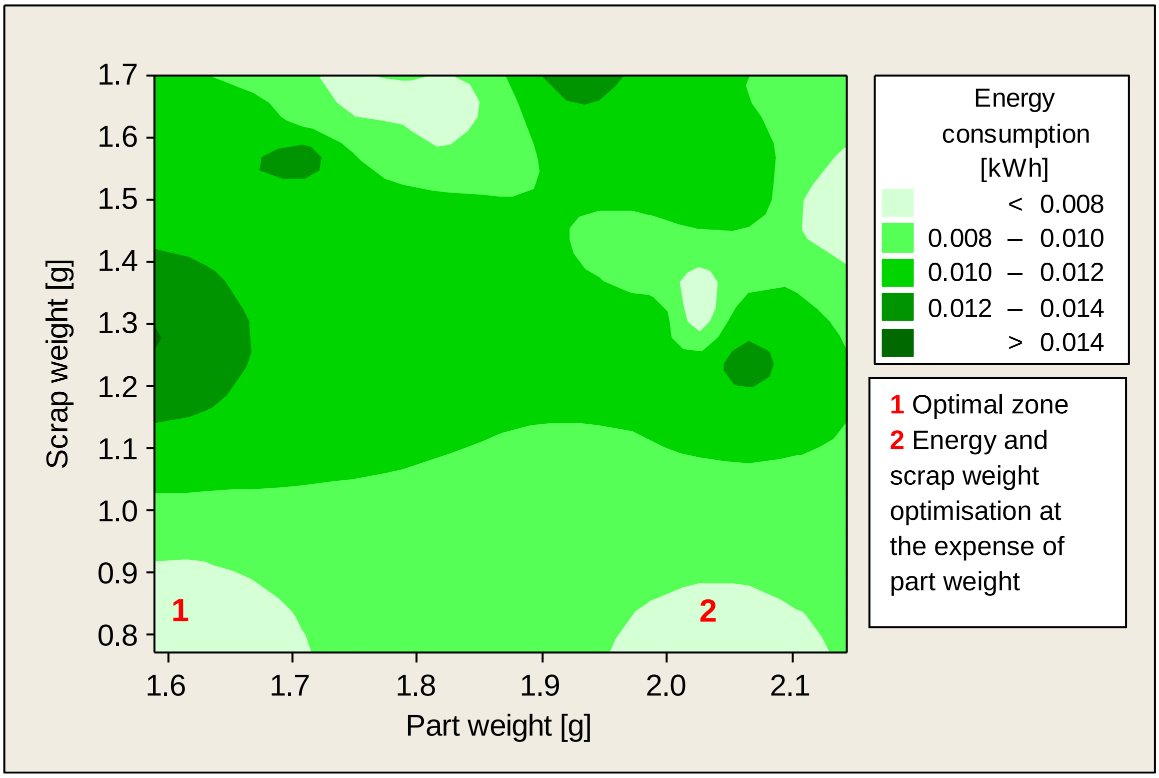


Figure 24. Contour plot of energy consumption vs scrap weight and part weight for tensile specimens.

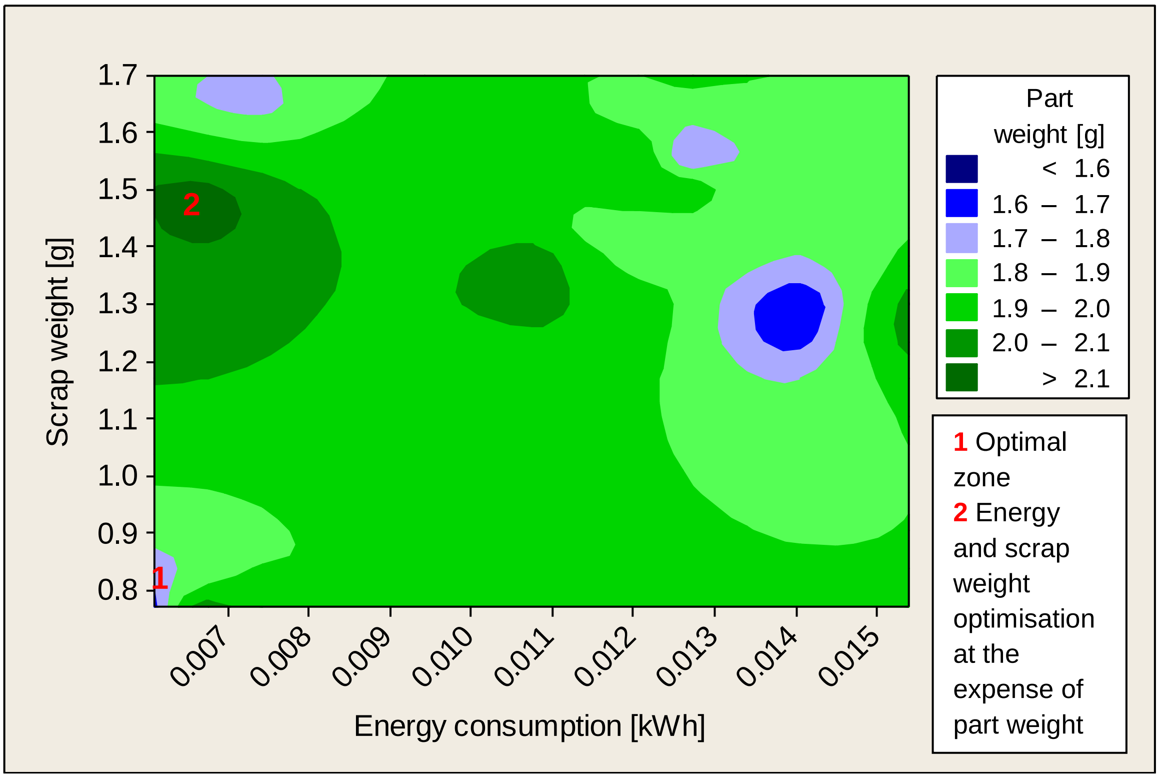



Figure 25. Contour plot of part weight vs scrap weight and energy consumption for tensile specimens.

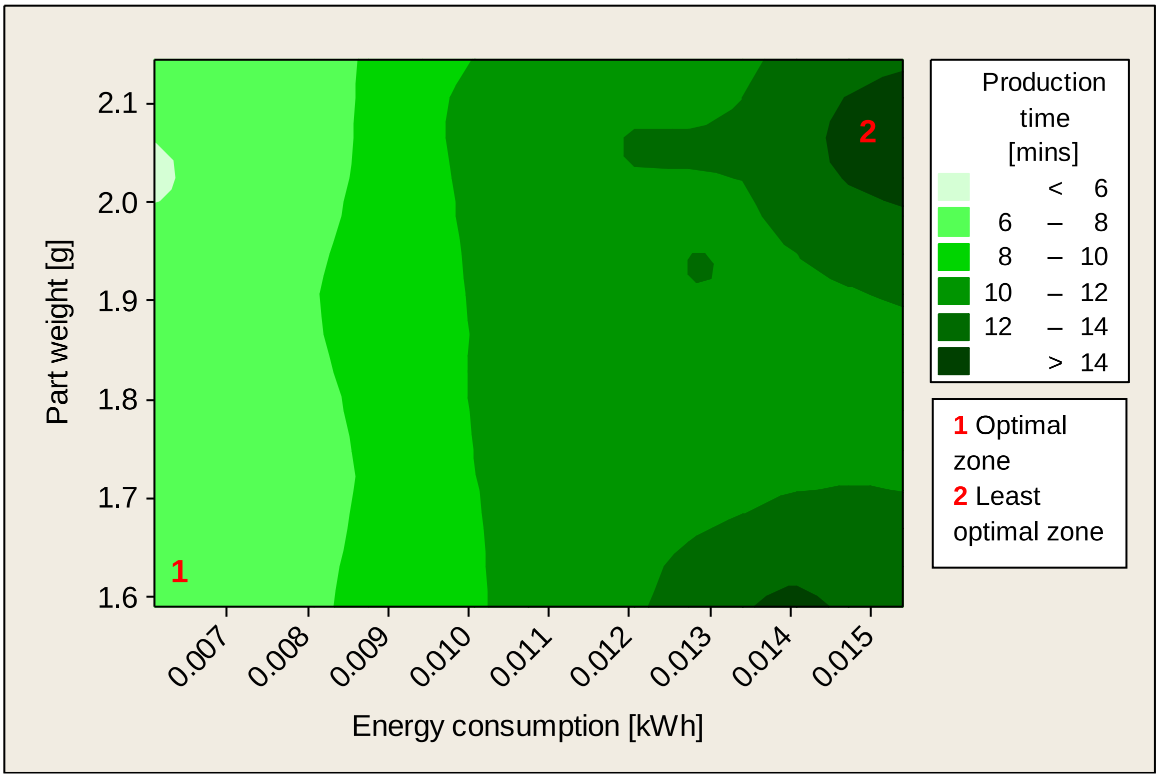



Figure 26. Contour plot of production time vs part weight and energy consumption for tensile specimens.

## 5. Conclusions

DDM has the possibility to produce personalised high quality products with the batch size of one. With affordable machines and open source software and digitalised skill acquisition, DDM and AM enable a wide spectrum of users. A populace empowered with the possibility of producing any products will have an entirely different impact on society and will inevitably lead to a change in energy and material consumption. Since production systems represent extremely complex environments it is unrealistic that all 3D printer users will have a consideration beyond part quality. However environmental and economic issues such as energy and material consumption, waste management, profitability per product, manufacturing costs and manufacturing time must be considered. By using a DOE approach this research has identified a method for identifying opportunities in balancing wasteful methods related to scrap weight, part weight, energy consumption and production time, and provides solutions for a more positive impact on sustainable development.

The main conclusions based on the obtained results are:

- Reducing the amount of scrap during manufacture saves money on material costs and waste disposal. The printed raft on the build plate on which the design is built is scrap material, Therefore, to minimise scrap weight, the part SO selection should be one where the part and build plate contact area is reduced. It is shown that the scrap weight is reduced dramatically with a change in SO, and determining the size of the raft for any given part is therefore the most important factor contributing to scrap. Designs with overhangs require a support structure which is also scrap material. Therefore, any SO for a reduced raft size should also consider the necessity of design features that overhang and thus require a support structure. A balance between the raft and support structure material must be considered when choosing a SO.

- Infill level, followed by the number of shells are the dominant factors that influence part weight for both the SENB and tensile test parts. Results show that an increase in infill and the number of shells results in a heavier part. Importantly, an interaction of the four control factors can be dominant in deciding the weight of a given part design. The FDM process can be optimised for lighter parts when production time and material usage is necessary and a part with increased infill and number of shells can be selected for improved mechanical properties.

- For energy consumption and production time the layer height is the most significant parameter. A lower height setting results in higher production time as there is an increase in the machine work from the x and y coordinate cycles to meet the design z height target. The interaction between these parameters can also be a significant influence.

- For both designs the most significant controlling parameter is the same for all four response outputs, and in the case of scrap and part weight the rank importance of the first two control parameters is the same. The results show that there are interactions of more significance than single control parameters. Therefore, when optimising a design with a particular parameter for a desired response, caution should be paid to the possibility of control parameter interactions.

- Depending on the required part specifications it is possible to identify settings for more than one desired response. A need for cost reduction requires reduced material and energy consumption and production time. Using the design of experiments approach it is possible to identify experiment settings that reduce all three (Experimental run 10 in Figure 15 and 16). This research thus showed a variation in the results for the two designs, so caution should be taken and an experimental approach for each design is necessary for process optimisation.

- The design of experiments approach can be used for co-operative optimisation of multiple responses. Decision making based on contour plots was used to explore the relationship between three variables, and decision making based on optimum requirements and regions of compromise were identified.

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**References**

Alexander, P., Allen, S., Dutta, D., 1998. Part orientation and build cost determination in layered manufacturing. Computer-Aided Design. 30, 343-356.

Anitha, R., Arunachalam, P., Radhakrishnan, P., 2001. Critical parameters influencing the quality of prototypes in fused deposition modelling. Journal of Materials Processing Technology. 118, 385-388.

Balogun, V.A., Kirkwood N.D., Mativenga P.T., 2014. Direct electrical energy demand in Fused Deposition Modelling. Procedia CIRP. 15, 38-43.

Boschetto, A., Bottini, L., 2014. Accuracy prediction in fused deposition modelling. International Journal of Advanced Manufacturing Technology. 73, 913-928.

Chen. D., Heyer, S., Ibbotson, S., Salontis, K., Steingrimsson, J.G., Thiede, S., 2015. Direct digital manufacturing: definition, evolution, and sustainability implications. Journal of Cleaner Production. 107, 615-625.

Crane, N.B., Tuckerman, J., Nielson, G.N., 2011. Self-assembly in additive manufacturing: opportunities and obstacles. Rapid Prototyping Journal. 17, 211-217,

European Environment Agency. The European Environment State and Outlook 2010; http://www.eea.europa.eu/soer. Accessed June 2016.

Garetti, M., Taisch, M., 2012. Sustainable manufacturing: trends and research challenges. Production Planning and Control. 23, 83–104.

Gebhardt, A., Schmidt, F.M., Hotter, J.S., Sokalla, W., Sokalla, P. 2010. Additive manufacturing by selective laser melting the realizer desktop machine and its application for the dental industry. Physics Procedia. 5 Part B, 543-549.

Gibson, I., Rosen, D.W., Stucker, B., 2010. Additive Manufacturing Technologies. Springer.

Griffiths C. A, Howarth J, De Almeida-Rowbotham G, Rees A. (2016). A design of experiments approach to optimise tensile and notched bending properties of fused deposition modelling parts. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 0954405416640182, first published on April 25, 2016

May, G., Barletta, I., Stahl, B., Taisch, M., 2015. Energy management in production: A novel method to develop key performance indicators for improving energy efficiency. Applied Energy. 149, 46-61.

Hon, K.K.B., 2005. Performance and evaluation of manufacturing systems. CIRP Annals - Manufacturing Technology. 54, 139–54.

Hopkinson, N., Dickens, P., 2001. Rapid prototyping for direct manufacture. Rapid Prototyping Journal. 7, 197-202.

Hopkinson, N., Dickens, P., 2003. Analysis of rapid manufacturing - using layer manufacturing processes for production. Journal of Mechanical Engineering Science. 217, 31-39.

Huang, R., Riddle, M., Graziano, D., Warren, J., Das, S., Mimbalkar, A., Cresko, J., Masanet, E., 2015. Energy and emissions saving potential of additive manufacturing: the case of lightweight aircraft components. Journal of Cleaner Production. In press, DOI 10.1016/j.jclepro.2015.04.109.

Ingole, D.S., Deshmukh, T.R., Kuthe, A.M., Ashtankar, K.M., 2011. Build orientation analysis for minimum cost determination in FDM. Journal of Engineering Manufacture. 225, 1925-1938.

International Energy Outlook 2013. International Energy Agency (IEA). http://www.eia.gov/forecasts/ieo/pdf/0484(2013).pdf. Accessed June 2016.

Kreiger, M.A., Mulder, M.L., Glover, A.G., Pearce, J.M., 2014. Life cycle analysis of distributed recycling of post-consumer high density polyethylene for 3-D printing filament. Journal of Cleaner Production. 70, 90-96.

Mognol, P., Lepicart, D., Perry, N., 2006. Rapid Prototyping - energy and environment in the spotlight. Rapid Prototyping Journal. 12, 26-34.

Monzon, M.D., Ortega, Z., Martinez, F., Ortega, F., 2014. Standardisation in additive manufacturing: activities carried out by international organizations and projects. International Journal of Advanced Manufacturing Technology. 76, 1111-1121.

Onwubolu, G.C., Rayegani, F., 2014. Characterisation and Optimisation of Mechanical Properties of ABS Parts Manufactured by the Fused Deposition Modelling Process. International Journal of Manufacturing Engineering. Article 598531.

Pham, D.T., Gault, R.S., 1998. A comparison of rapid prototyping technologies. International Journal of Machine Tools and Manufacture. 38, 1257-1287.

Raut, S., Jatti, V.S., Khedkar, N.K., Singh, T.P., 2014. Investigation of the effect of built orientation on mechanical properties and total cost of FDM parts. Procedia Materials Science. 6, 1625–1630.

Rayegani, F., Onwubolu, G.C., 2014. Fused deposition modelling (FDM) process parameter prediction and optimization using group method for data handling (GMDH) and differential evolution (DE). International Journal of Advanced Manufacturing Technology. 73, 509-519.

Sood, A.K., Chaturvedi, V., Datta, S., Mahapatra, S.S., 2001. Optimisation of process parameters in fused deposition modelling using weighted principal component analysis. Journal of Advanced Manufacturing Systems. 10, 241-259.

Sood, A.K., Ohdar, R.K., Mahapatra, S.S., 2009. Parametric appraisal of mechanical property of fused deposition modelling processed parts. Materials and Design. 31, 287-295.

Sood, A.K., Ohdar, S.S., Mahapatra, S.S., 2009. Improving dimensional accuracy of Fused Deposition Modelling processed part using grey Taguchi method. Materials and Design. 30, 4243-4252.

Tang, Y., Mak, K., Zhao, Y.F., 2016. A framework to reduce product environmental impact through design optimization for additive manufacturing. Journal of Cleaner Production. In press, DOI 10.1016/j.jclepro.2016.06.037.

Thrimurthulu, K., Pandey, P.M., Reddy, N.R., 2004. Optimum part deposition orientation in fused deposition modelling. International Journal of Machine Tools and Manufacture. 44, 585-594.

Wang, S., Fang, C., Guan, X., Pang, B., Ma, H., 2014. Urbanisation, energy consumption, and carbon dioxide emissions in China: a panel data analysis of China’s provinces. Applied Energy. 136, 738–49.

Willimams, C.B., Mistree, F., Rosen, D.W., 2011. A Functional Classification Framework for the Conceptual Design of Additive Manufacturing Technologies. Journal of Mechanical Design. 133, 121002-121002-11.