Economic Analysis of Plastic Additive Manufacturing for Production of End Use Products: A Preliminary Study

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ABSTRACT
Additive Manufacturing (AM) has enjoyed a rapid development over the past decade, and the improved process capability brings a number of attractive potentials for direct manufacturing of end use components and products. However, there is a lack of assessment for the economical use of this novel technology. This paper reports on an initial study focusing on the economic viability of using plastic AM as a production method for low to high volume production. A test product was designed and the AM production costs were obtained from ten AM service providers across Europe, which were further compared with injection moulding and vacuum casting. The analysis results show that AM is economically viable for low to medium batch production for up to 100 parts, which could save up to two third of the production cost per part compared with injection moulding. This indicates that plastic AM has the potential to be a bridge to higher volume production.

KEYWORDS: Additive Manufacturing; Costing; Economic Viability; Selective Laser Sintering; Fused Deposition Modelling

1. INTRODUCTION

Additive Manufacturing (AM) has been receiving increasing attention in the past twenty years and this growth has been made possible by continued improvements in AM processes and materials [1]. Compared to conventional manufacturing processes, AM offers enormous potentials in manufacturing complex part geometries, reducing lead times and associated cost, which makes it become an economically viable method for low volume production of end use components and products [2]. In order to leverage the advantages of AM, designers need to conceive and design the product according to the characteristics of the selected AM process in the very early stages of the product development process [3]. However, it is not always cost effective to manufacture parts using AM. Selecting an appropriate manufacturing process involves trade-offs in part quality, production time, volume and the consequent cost such as tooling cost. A typical example is injection moulding (IM). Despite huge investment on tooling being necessary, high and consistent part quality such as dimensional accuracy, surface finish and strength is achievable and the unit cost of the part is reduced exponentially when increasing the production volume. There has been some research investigating process selection but mostly between AM processes rather than between AM and conventional processes. In addition, costing remains commercially secret and there is no data publicly available for decision makers and designers to choose an appropriate manufacturing process in terms of production volume and cost. This study aims to assess the economic viability of the two most widely used plastic AM technologies, namely fused deposition modelling (FDM) and selective laser sintering (SLS). A test product was designed, consisting of components with different sizes. The costs of producing the test part with four quantities i.e. 1, 10, 100 and 1000-off were obtained from AM service bureaus across Europe, which were then compared with the costs of IM and vacuum casting (VC). The economic production volume for AM is suggested, demonstrating that FDM and SLS technologies are competitive candidates for low to medium volume production.

2. LITERATURE REVIEW ON AM PROCESS SELECTION

In recent years, AM has evolved from a rapid prototyping tool to a viable manufacturing method for customised products and low volume production. As AM family includes more than 10 different techniques, a number of theoretical models have been developed to help designers choose an appropriate AM process based on part geometry, material and production cost. There have been a number of key studies in this area over the last 5 years:

- Vinodh et al. [4] employed a fuzzy algorithm to enable process selection between competing AM technologies taking four factors into consideration: part size, geometry, process capability and production rate.
- Conner et al. [5] presented a framework to identify the scenarios where AM is a suitable alternative to conventional manufacturing processes. The framework consists of eight regions with three different factors, which are customisation, geometry complexity and production volume. Combining the factors with varying levels (i.e. low, medium and high) leads to eight regions, amongst which only the region i.e. low complexity, low customisation and high volume is considered to be unsuitable for AM production; while the other regions show the potential for AM applications.
- Munguía et al. [6] proposed a Rapid Manufacturing Advice System to support designers during the early stages of a design process to assess the possibility of using AM as the final manufacturing route. The input parameters are classified into three types: design related (e.g. dimensions, volume, shape, surface finish); production related (e.g. batch size, production rate); and processing/materials related (e.g. printing speed, chamber temperature and tensile strength etc). Based on the ranking of the design requirements and input parameters, different AM technologies can be compared.

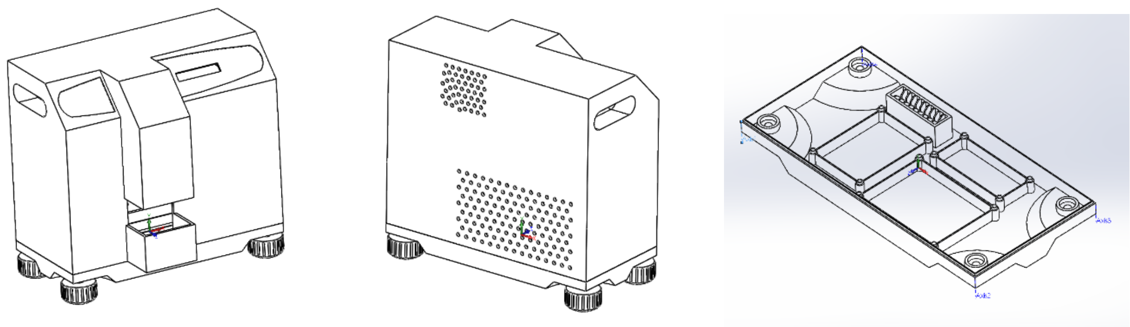
These three papers focus mainly on process selection, with little consideration of the cost implications. Baldinger et al. [2] and Atzeni and Salmi [7] both seek to explore the cost implications of AM. Baldinger et al. [2] proposed a preliminary qualitative cost estimation model for SLS and Selective Laser Melting (SLM) using cost matrices. The benchmark of the model was based on the service provider quotation data. However, the economic production volume in comparison to conventional processes was not identified. Atzeni and Salmi [7] analysed the production cost of SLM of aluminium alloys and divided it into three categories, namely, SLM machine cost, manufacturing cost (including material cost, pre-processing, processing and post-processing costs) and labour cost. The cost estimation result suggests that the quantity of 42 parts is the breakeven point, beyond which using SLM is no longer an economic solution compared with high pressure die casting (HPDC). Atzeni and Salmi's study [7] focuses on a niche application i.e. aerospace where AM has already claimed extraordinary benefits, rather than the wider field of manufacturing industries for direct production of end use industrial and scientific products.

3. METHOD

This paper analyses the economic viability of plastic AM through comparing the production cost with two traditional processes i.e. injection moulding and vacuum casting for different production volumes. The reasons of choosing these two traditional methods are: (i) injection moulding is the most common mass production process capable of producing high quality plastic products with varying sizes; and (ii) vacuum casting is a cost effective method for medium production volume. A product was specifically designed, consisting of three different components with the sizes ranging from small to large (please refer to section 4 – the product design). The production costs for printing the product using FDM and SLS were obtained from ten European service providers and transferred to sterling. Four typical levels of production volumes are assessed, from quantities of 1 to 1000.

4. THE PRODUCT DESIGN

A bench top scientific instrument has been designed, as shown in Figure 1. The instrument is comprised of a case, a base (Figure 1c) and four feet. The sizes of the case, the base and the foot cover the volume range from small to large for AM parts, which are 250×199.9×160 mm^3 (L×W×H), 250×22×120 mm^3 and 37×37×47 mm^3, respectively. The case is a hollow part, which is designed to house electronics. The materials for SLS and FDM are Nylon and ABS, respectively.



(a) (b) (c)

Figure 1: The design of the bench top scientific instrument: (a) front (b) back (c) base

4. RESULTS AND DISCUSSION

Five SLS and five FDM service bureaus were approached and requested for quotation for producing base, case and foot for the quantities of 1, 10, 100 and 1000 units. The average unit costs of FDM and SLS are plotted in Figures 2 to 4 below, together with the costs of IM and VC obtained from two service providers. It is noted that the production volume starts with 25 units for IM and VC as they are not a common method for one-off part production.

It is found that, for both SLS and FDM parts, the unit cost reduces significantly when production volume increases from 1 to 10. Further raising the quantities to 100 and 1000, though the unit cost keeps falling, there is no significant changes and the price per unit is virtually stable, especially for FDM parts. For small and medium part sizes, SLS is much cheaper than FDM with the biggest price difference being approximately £33 per foot and £40 per base. This is partly due to the nature of the build in SLS where parts can be stacked with each other until the build chamber is filled up both horizontally and vertically, which efficiently utilises the material and space. Whereas, objects can only be laid out horizontally on a build platform in FDM, resulting in less number of parts to be printed in one build. However, if the part size gets larger and the geometry consists of a large enclosure such as the geometry of the case, FDM turns out to be more cost effective than SLS. This is because creating an enclosure essentially requires printing the walls as well as the space inside of them, leading to rather low material usage. The material cost itself, unfortunately, is a significant factor that contributes to the total SLS production cost. It should also be noted that building a large, particularly high and thin object is challenging for FDM due to the limited build chamber size and low accuracy in the vertical direction. Therefore, only three of the five FDM service bureaus were able to produce the case.

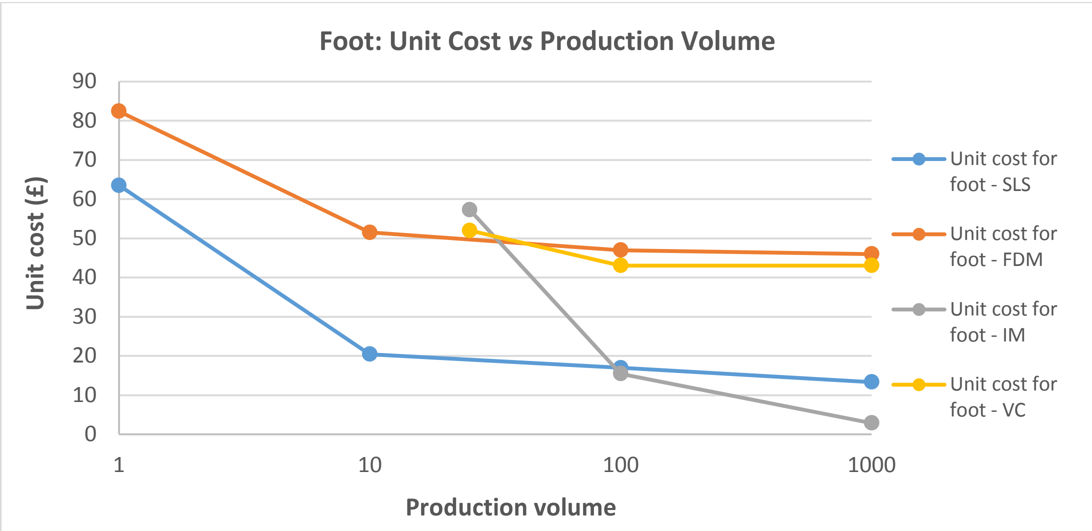


Figure 2: The average unit cost for producing a foot (small part size)

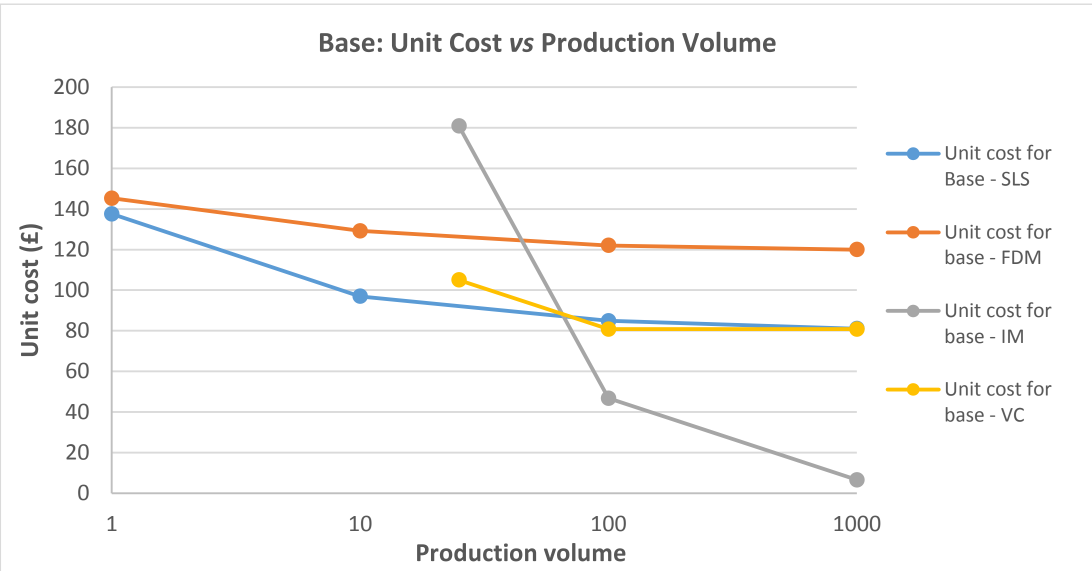


Figure 3: The average unit cost for producing a base (medium part size)

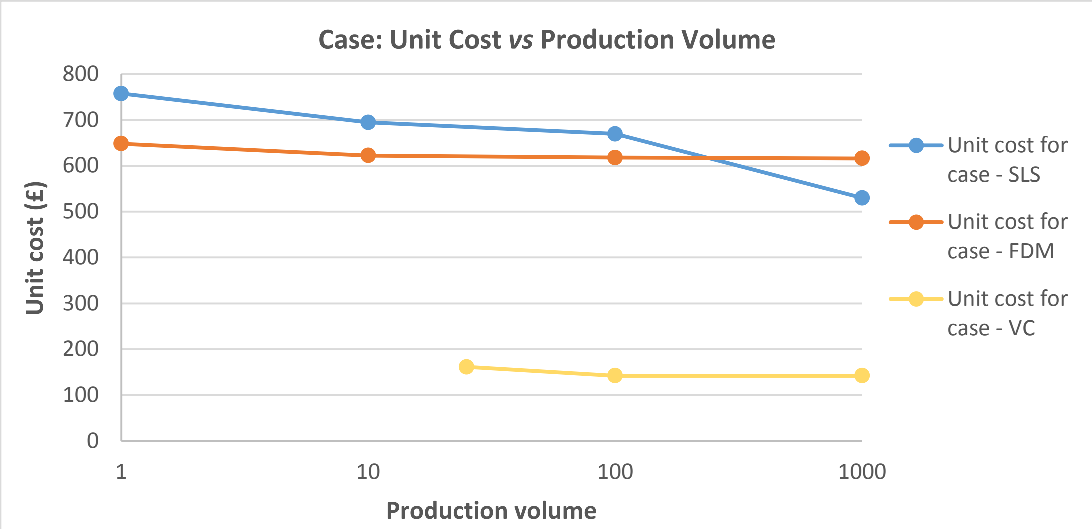


Figure 4: The average unit cost for producing a case (large part size)

Different from the cost variation of FDM and SLS parts for different production volumes, the actual cost for injection moulding a single part is the same no matter how many of them are going to be made. The tooling cost dominates the expenses spent in IM, and as long as the mould is made properly, it can be used over hundreds of thousands of production runs. In terms of the cost per item by taking tooling into account, the high tooling cost cancels out along with the increased production volume. From Figures 2 and 3, it can be identified that, despite the unit cost being the highest between the four processes, IM starts to show the economic viability for the quantity of over 100 parts. The unit cost drops significantly when the production volume reaches 1000, indicating that as long as the tooling cost pays off, IM is still the ideal candidate for mass production of plastic products. Moreover, there is no IM quote for the case since the size of it is larger than the size limit that the service provider is capable of producing. Thus, separate moulds need to be made, resulting in higher cost.

In addition, vacuum casting is a competitive process for low to medium volume production i.e. quantity of less than 100 parts. Figures 2 and 3 suggest that, when fabricating 25 parts, the unit cost of the foot by VC is only slightly higher than FDM, and the unit cost of the base by VC is even lower than FDM but higher than SLS. As the production volume raises to 100-off (as shown in Figure 3) or the part size increases (e.g. the case in Figure 4), VC turns out to be financially better than either SLS or FDM. However, it is worth mentioning that the turnaround time for VC in this case requires 4 weeks including creating the mould by stereolithography and using the mould for casting, which in most cases is longer than that of using FDM and SLS as the production processes.

Figures 2 to 4 demonstrate that the economic viable production volume for both FDM and SLS is 10 to 100-off. The quantity of around 20 parts is considered to be a sensible cost cut off, beyond which the unit cost will not largely reduce. Additionally, production cost tends to be less competitive when the object gets bigger (e.g. 8×10^3 cm^3), particularly with enclosures that require large amount of support material such as the case (see Figures 3 and 4). This finding is contradictory to the simulation results by Atzeni et al. [8] who identified the breakeven quantity for SLS and IM of small components with the size of $15.3\times19.5\times28.2$ mm^3 was around 70,000 to 80,000 pieces. However, it should be clarified that AM production cost does not only lie on production volume and part size. It is also geometry and material dependent. Thus, two years later, Atzeni and Salmi [7] in 2012 designed another test part and compared SLM with HPDC and the breakeven point was found to be 42 pieces, which is consistent with the finding in this study. This demonstrates the potential of AM to be a bridge to higher volume production such as IM. Nevertheless, two limitations in this study should be addressed. Firstly, the quotes were obtained from the bureaus who always tried to maximise profit by doing high volume for different parts for different clients. They are reluctant to commit to printing identical parts for a single client due to machine availability and utilisation considerations. The actual cost is likely to be different if the client him/herself owns an in-house AM machine. Secondly, the bureaus usually try and stack different parts together as many as possible within the build chamber in order to achieve better economy. The quotes thus do not guarantee the best print quality due to for example orientation not being optimised.

5. CONCLUSIONS

The rapid technology development has enabled AM to be considered as a feasible production method due to its ability to manufacture high quality products with a reasonable cost and short turnaround time. This paper explored the financial viability of SLS and FDM for low to high production volumes of up to 1000 parts. A test product was designed, consisting of three different components with varying sizes. The production costs were obtained from a number of service bureaus and compared with injection moulding and vacuum casting. The results indicate that FDM and SLS are economically viable for the volume of up to 100 parts, particularly for small size components e.g. 6×10^4 mm^3. The cost by SLS was found to be lower than FDM for small to medium size parts and a single SLSed foot can save up to 2/3 cost compared to injection moulding when making 25 feet. However, for the volume higher than 100 parts, the cost per part by FDM and SLS remains flat, in which case injection moulding becomes the preferred manufacturing process as the extremely low unit cost for thousands of parts justifies the high tooling cost. Future work will focus on investigating a robust decision-making system that is able to identify an AM process suitable for a certain production volume based on a given part design and material.

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