A FRAMEWORK FOR DESIGNING END USE PRODUCTS FOR DIRECT MANUFACTURING USING ADDITIVE MANUFACTURING TECHNOLOGIES

Zhu, Zicheng (1); Pradel, Patrick (2); Bibb, Richard (2); Moultrie, James (1)
1: University of Cambridge, United Kingdom; 2: Loughborough University, United Kingdom

Abstract

Additive Manufacturing (AM) has enjoyed rapid development over the past decade and improved process capability brings attractive potentials for direct manufacturing of end use components and products. This opens a new avenue for designers to design a much wider variety of products in a more time and cost effective way. A new research field – design for AM – is emerging, exploring new design principles, methods and rules. However, the vast majority of the methods and rules presented to date focus on the feature level, which are specifically applied at the detail design stage to ensure the manufacturability of the features for a given AM process. This does not enable designers to fully benefit from unique AM capabilities. Therefore, this paper proposes a framework that holistically considers design freedoms, AM advantages and limitations for designing end use products, providing guidance throughout process selection and different design stages. The major considerations in the design process are addressed, showing effective ways of making use of AM. Process characteristics, design rules and implications of using AM on product shape, quality and economic viability are also described.

Keywords: Design for Additive Manufacturing (DfAM), Additive Manufacturing, Design process, Fused Deposition Modelling, Selective Laser Sintering

Contact:
Dr. Zicheng Zhu
University of Cambridge
Department of Engineering
United Kingdom
zz330@cam.ac.uk

1   INTRODUCTION

Additive Manufacturing (AM), also referred to as 3D printing, is revolutionising the way products are designed and manufactured. AM creates objects in a layer-by-layer manner, enabling complex geometries to be produced (Gao et al., 2015). AM was first used as a prototyping tool for designers to facilitate and accelerate the product development process. With continued advancement, AM has now shown huge potential to become an economically viable series production method particularly for low volume production of end use products (Wohlers, 2015). However, one of the most significant barriers for successful commercialisation of AM technologies is the lack of knowledge amongst designers on how to design components which not only are additively manufacturable but also leverage the advantages of AM for direct manufacturing (Thompson et al., 2016). This essentially requires Design for AM (DfAM) knowledge to be developed, enabling the transition of AM from rapid prototyping to a mainstream production method.

Despite significant attention having been paid to DfAM research in the past few years, most studies centre on the 'feature level', namely, refining design details such as wall thickness to ensure the manufacturability of the designed component for a given AM process. There is a lack of broader design guidance that holistically considers AM process characteristics as well as the impact on design, subsequent manufacturing and post-processing.

This paper proposes a DfAM framework for designing end-use components and products. It covers the major design considerations in the entire design process. The data that forms the foundation of the framework was collected from interviews with professional designers and AM practitioners who have significant experience of designing products for AM. The methodology used for data collection is first introduced, followed by the description of the framework. The major elements of the framework are elaborated in more detail before the impact of AM on design and production are discussed.

2   LITERATURE REVIEW ON DESIGN FOR ADDITIVE MANUFACTURING

In the past five years, there has been a rapid growth in the number of publications examining aspects of DfAM. It is evident that within the broader topic of 'additive manufacturing', this is an emerging and rapidly changing field and one in which concepts and ideas are still forming.

The major review papers so far include Gibson et al. (2015), Yang and Zhao (2015) and Kumke et al. (2016). Gibson et al. (2015) reviewed the recent advances in DfAM and identified the advantages of AM in producing complex geometry, integrated assemblies, customised geometry, multi-functional products and lightweight structures. Yang and Zhao (2015) presented a comprehensive review on AM-enabled design theory and methodology. A number of design rules and topological optimisation methods are summarised, taking process capability and part geometry into consideration. More recently, Kumke et al. (2016) classified DfAM research into two categories: DfAM in the strict and broad senses. DfAM in the strict sense includes approaches tailored to the core design process, e.g. design rules for ensuring AM-producible parts. On the other hand, the methods related to process selection, production strategy and manufacturability analysis are considered to be DfAM in the broad sense.

DfAM research for conceptual design is mainly concerned with concept generation and selection. The first attempt to provide a DfAM tool for conceptual design was made by Rosen (2007), who proposed a biomimetic approach. This was aimed at helping designers search solutions and engineering principles from the working principles in biological systems. Salonitis (2016) proposed a framework based on an axiomatic design method, which is able to assess design ideas by taking AM capabilities and limitations into account. The axiomatic design method addresses customer needs in terms of product functions to choose design solutions and associated parameters.

DfAM for embodiment design investigates guidelines and tools for (re)designing features or components, utilising AM advantages whilst ensuring manufacturability. Schmelzle et al. (2015) developed a redesign method for part consolidation, including the following key steps: (i) defining redesign space; (ii) specifying internal and external geometry; (iii) identifying the build orientation to minimise build time and material usage; (iv) specifying build supports and (v) identifying post-processing needs. A hydraulic manifold was redesigned, which simplified the original 17 pieces into a single component, realising 60% and 53% reductions in weight and height, respectively.

Detail design rules are primarily used to refine or optimise features according to the capability of the specific AM process to be used. The most representative research is by Adam and Zimmer (2015) and

Kranz et al. (2015) where a set of detailed rules identifying feature types in relation to dimensions were obtained. Adam and Zimmer (2015) conducted a series of 3D printing tests to investigate the relationships between feature dimensions and AM process parameters in terms of dimensional accuracy and surface quality. Typical features include wall thickness, outer and inner edges, slot depth, width and length, and overhang length. Similarly, Kranz et al. (2015) explored detail design guidelines covering a wide range of prismatic features such as cavity, cylinder, wall and bore.

Although significant efforts have been made to explore design methods and rules for AM, arguably the majority of the research lies in developing detail design rules. Most of the rules are only for checking and ensuring manufacturability of designed features for specific AM processes rather than exploiting the full potentials of AM. There is a lack of a holistic method for the entire design process that considers both AM capabilities and limitations as well as the resulting design freedoms and constraints. In addition, the developed methods such as topological optimisation methods, though utilising some unique AM advantages, are largely based on manufacturing point of view. At present, little attention has been paid to investigating current design practice adopted by designers and the impacts of AM technologies in the way components and products are designed and directly produced.

3 METHODOLOGY

Exposure to a broad range of design practice adopted by professional designers and AM practitioners was sought and so interviews were used to explore designers' experience in designing end use products for AM production. Finding designers with experience of DfAM was a significant challenge, as very few designers had actually designed products specifically for AM due to the fact that AM technologies, as emerging series production methods, are still relatively immature. Over the course of three months 17 UK-based industrial designers were interviewed. They were identified using three sources: (i) the partners of this research project; (ii) participants who completed the online survey entitled 'Design for Additive Manufacturing survey' that was conducted previously and (iii) using referrals from previous interview participants. All of the designers had significant professional design experience (ranging from 3 to 30 years) and most of them had significant experience in DfAM. In total, the participants were associated with 10 different companies including freelancers, design consultancies, a service bureau, research institutions and a multi-national engineering corporation.

11 structured interviews were conducted (participants from the same company were either grouped or individually interviewed depending on their preferences), with a mean duration of approximately 70 minutes. Each interview comprised four parts: (i) general experience of AM; (ii) component/case examples; (iii) General reflections on AM as a production process and DfAM; and (iv) designer's background. Each interview was centred on the discussion of a component(s) or product(s) which were specifically designed for production using AM, exploring the design considerations, rationale and limitations etc. This study focuses on plastic components and products manufactured by either selective laser sintering (SLS) and/or fused deposition modelling (FDM). With the interviewees' permission, each interview was recorded and later transcribed to produce over 200,000 words of text-based data. Computer-aided qualitative data analysis software QSR NVivo 10 was used to assist in storing, structuring and analysing the interview data. Useful information relating to DfAM, such as design concepts, methods and rules used, were extracted and classified into groups. By constantly comparing the emerging interpretations with the source material conducted by two independent researchers, a number of different concepts, categories and competing frameworks were produced. We aimed to report with high fidelity what the designers said and how the products were designed. Therefore, the framework presented and described in the reminder of this paper is considered a faithful and coherent representation of the collected data.

4 THE DFAM FRAMEWORK

The DfAM framework that resulted from the study is shown in Figure 1, which is built using the IDEF0 functional modelling method, consisting of five parts: (i) process selection; (ii) design process; (iii) control factors for generating the design (e.g. AM process characteristics and design rules); (iv) resources (i.e. designer's DfAM knowledge); and (v) impact of AM on design process. The solid arrows represent a principal impact and the dotted arrows denote a secondary impact.

The framework streamlines the design process by considering design guidelines, rules and various influential factors including AM process characteristics, designer's knowledge and economic

considerations, etc. Upon receiving the design requirements, an appropriate manufacturing process needs to be first identified. This requires a thorough consideration of process capability in relation to product shape, mechanical properties, production cost and time (see Section 5.1). If AM is considered to be a viable production route, the specific AM technique needs to be selected, which will be presented in Section 5.2. Having chosen the suitable AM process, the designer will typically follow the standard process starting from conceptual, through embodiment to detail design. In order to make good use of AM rather than merely designing a product that is 3D printable, special attention should be paid to each design stage, for example, incorporating small and neighbouring components in the conceptual design (Section 6). When designing the product, designers also need to follow certain design guidelines and rules (Section 8) whilst bearing in mind the wider impact of the components designed for AM on the other components of the product which are designed to be made by conventional processes (Section 9). Furthermore, designer's knowledge on DfAM ranging from design, AM processes and materials to production is the essential resource for effectively completing the design process (Section 10). The use of AM as a production technology is deemed to have a far-reaching influence on product design and manufacture, which is discussed in Section 11.
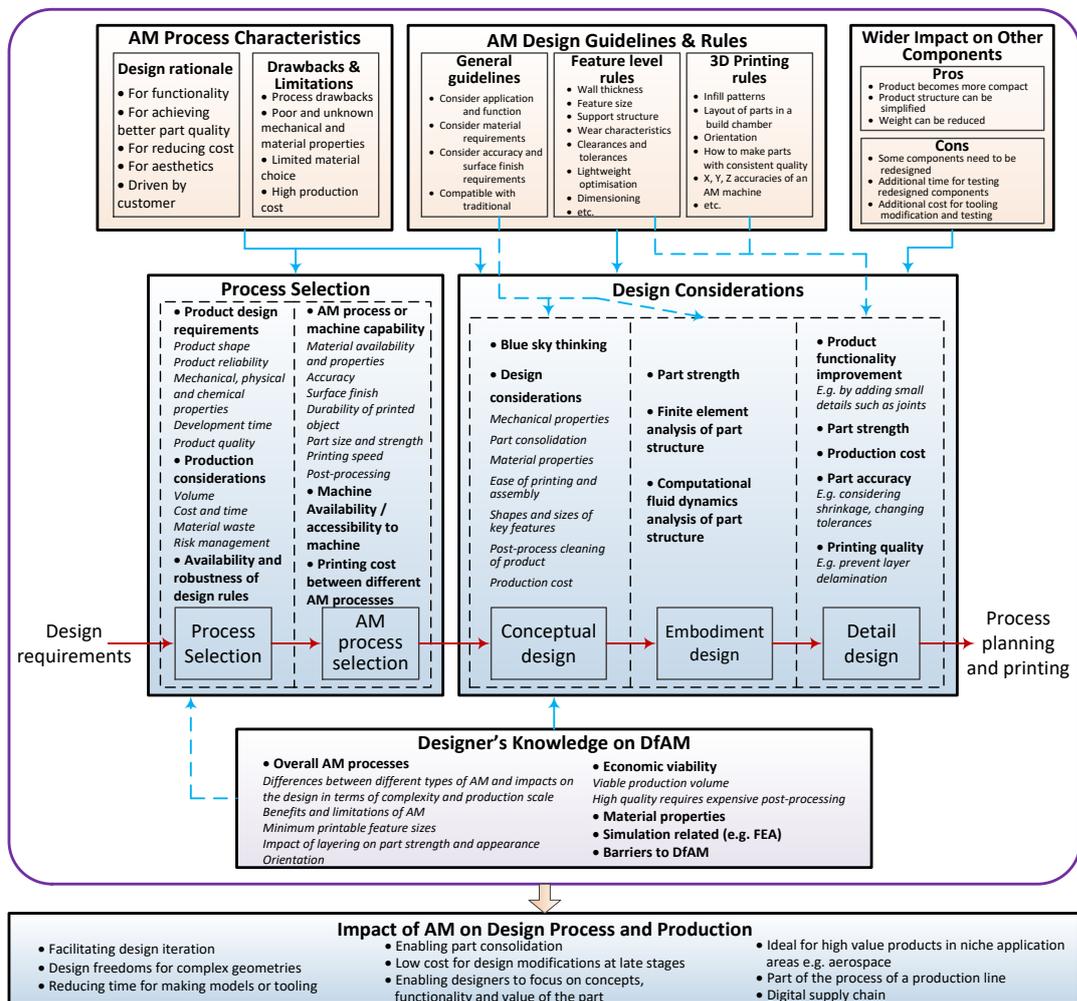

Figure 1. The framework for designing end use components/products for AM

The framework described above is intended to represent a typical DfAM design process adopted by designers and AM practitioners in a coherent way whilst remaining faithful to the data collected in the interviews. Where helpful, quotations are drawn from the interview transcripts to illustrate, clarify or support the framework. Each quotation is followed by an anonymised interviewee identifier.

5 PROCESS SELECTION

Process selection is the first stage prior to the actual design process. A sensible selection of processes from a wide range of manufacturing methods is mostly based on product requirements such as shape,

surface quality, material and functionality, production volume and budget. This section divides process selection into two steps: (i) determine whether to use AM or a conventional process; and (ii) choose a specific AM technique if AM is going to be used.

5.1 Process selection between conventional and AM processes

The three dominant clusters that determine process selection are: (1) product design requirements; (2) production considerations; and (3) availability and robustness of design guidelines and material data sheets.

5.1.1 Product design requirements

In the design brief, the requirements for the new product are specified, including product shape, mechanical, physical and chemical properties, quality and product development time scale. AM is well known for its capability to produce complex geometries, which makes it an ideal candidate for applications where ergonomic requirements and aesthetic appearance are priorities. However, the parts produced by conventional manufacturing techniques can achieve far better quality in terms of surface finish, dimensional accuracy and more importantly part consistency. One of the major drawbacks that hinder the widespread application of AM technologies for series production is poor process consistency, leading to printed parts having significant dimensional deviations. The criteria to be considered in product properties include weight reduction, strength, durability and chemical compatibility. Printing hollow or lattice structure can dramatically reduce weight, whereas, designers are concerned with the unknown durability of the printed products when they are repeatedly used and exposed to direct daylight, high or low temperatures, humid environments, etc.

5.1.2 Production considerations

Production considerations are mainly related to economic viability including production volume, cost, time, material waste and risk management. Interviewees indicated that the viable production volume for AM is around 50 - 100 pieces, depending on size. Both AM production cost and time are significantly lower compared with traditional processes when making products at these low quantities. Time savings can be achieved by printing pre-assembled parts and eliminating tooling needs. AM might be particularly suitable at product launch, especially for a small company that has a limited budget or resources and heavily relies on a third party supply of components which they cannot guarantee for any length of time.

5.1.3 Availability and robustness of design guidelines and material data sheets

Designers are more willing to design a product for injection moulding (IM) if it is plastic or for machining or casting if it is metal. This is primarily because, for those traditional processes, robust and extensive design rules are well-established. Whereas, there has not been a comprehensive set of AM design rules and material data sheets that designers can rely on.

'Our initial concerns were the cost, the consistency of the parts with different built types, what would happen to the parts over a long period of time, would they wear badly, would they break up, would they become brittle and fracture; the surface finishing - the quality bit. And at the time, there were no guidelines for design and we were looking at this thing which without going into the details; thin wall section in the middle of the pivot point may lead to the failure of the build; material properties – not strong enough i.e. strength.' (ID08, engineering device).

5.2 AM process selection

AM represents a family of layered manufacturing techniques which share some common features e.g. building an object layer-by-layer, but each technique has its unique characteristics and drawbacks. After deciding to use AM for production, the specific process needs to be identified. The selection criteria can be categorised into the following three groups:

- AM process or machine capability: This involves a number of factors, including accuracy, surface finish, part size (both the largest size and the finest feature size achievable), printing speed, part strength, durability of printed object (if known), post-processing considerations e.g. support material removal and sterilisation for medical applications.

- Machine availability / accessibility to machine: From the interviewees' responses, machine availability is one of the major factors in AM process selection. For designers, to a large extent, they are tied to the AM machines that they have or their suppliers have in house.
- Printing cost: depending on the part size and quantity, the printing costs of different AM processes may vary greatly.

'I looked at FDM, material jetting and laser sintering; but the end choice was laser sintered because of the material, finish, no support structures to remove, and cost - because machine productivity is much better for laser sintering than FDM.' (ID04, engineering device).

6 DESIGN CONSIDERATIONS

This section presents the considerations that can be used as a reference to facilitate product design and make the most of AM advantages.

6.1 Design considerations at conceptual and embodiment design stages

Two contradictory standpoints have been identified in this study: 30% of the interviewees were of the strong opinion that the nature of conceptual design is blue-sky thinking and thus designers should be completely free and not be constrained by specific manufacturing processes. Whereas other interviewees argued that, given the uniqueness of AM, some process-related factors need to be taken into account, including the potential for part consolidation, ease of printing and assembly, mechanical and material properties, shape and size of each key feature (e.g. usability for customers, and fitting into an existing instrument), post-process cleaning of the material. In addition, most designers found conceptual design for AM is particularly challenging as they currently rely on previous experience and tacit knowledge which are typically gained through trial and error.

'The great thing we were able to do at the concept stage was to be able to combine several parts into one part, which make it more durable, which make it easier to build, it makes it easier to assemble. And that was the main thing, was conceptually being able to make the entire thing as one pre-built assembly in SLS, rather than have to make it out of ten different parts which then had to be bolted together.' (ID08, engineering device).

From the interviews, it is noted that there is no clear boundary between conceptual and embodiment design stages. Some interviewees considered part consolidation and mechanical properties in embodiment design. In addition to this, more specific methods are mentioned, which are finite element analysis and computational fluid dynamics, to analyse product performance and ensure sufficient strength.

6.2 Design considerations at detail design stage

Most of the considerations for detail design identified from the interviews were found to be consistent with the literature. These considerations include part accuracy, printing quality, product functionality, part strength and production cost. Due to the significant temperature difference during and after printing, material shrinkage needs to be addressed, which requires using appropriate tolerances and clearances to ensure part accuracy. In terms of printing quality, designers should be very mindful and aware of lamination effects and anisotropy. In detail design, small features such as mounting points and pivot points can be added in order to further improve product functionality.

'It is still layered manufacturing, you still can see pronounced layers although they are bonded very well you still get layers and still is a potential failure.' (ID02, engineering component).

Although product cost has already been considered in the previous design stages, designers are still encouraged to make minor changes in detail design as it can potentially lead to significant cost reduction.

'A lot of people want to make enclosures, enclosures automatically include space, and that's not a very economically efficient work to make things easy…it's through additive manufacturing. If it's in FDM, both spaces are gonna [sic] be full of support, one way or another. If it's in SLS, you are just wasting powder…we suggest that they break them down. The box, for example…if it's some kind of special box, just print it as six flat panels and design it to come together so that you are not printing the space.' (ID07, consumer product).

7 AM PROCESS CHARACTERISTICS

Designers need to keep AM process characteristics in mind while selecting a manufacturing process and designing the product for the selected process. These characteristics have both an upside that designers need to effectively utilise and a downside that needs to be circumvented.

7.1 Design rationale

During the interviews, the designs of the example parts provided by the participants were discussed, exploring the design rationale. It was found that the main drivers when designing for AM are functionality, part quality and production cost. A typical example is to utilise the capability of producing complex and pre-assembled parts.

'I took out any components that were no longer needed like O-rings and joined the CAD files together into one model. I then got rid of any features that were purely there for conventional processes like drafts. I think I probably thickened up some features for strength.' (ID04, engineering device).

7.2 Drawbacks and limitations as a result of designing for AM

Although AM is advertised as being able to provide significant design freedoms, there are in fact several limitations and drawbacks that hold designers back. These include process drawbacks, poor or unknown mechanical and material properties, limited material availability and high production cost. These drawbacks are fundamentally associated with current AM process capabilities and limitations.

The five notable process drawbacks are: (1) orientation in relation to part quality; (2) wall thickness; (3) dimensional accuracy and surface finish; (4) process repeatability; and (5) post-processing. Amongst these drawbacks, most of the interviewees were concerned about accuracy and surface finish, orientation, and process repeatability. In addition, using different orientations might significantly affect part accuracy, surface quality and part strength etc.

'So that goes for the direction you are printing as well. So the example of the [product], you can see there are a few defects around quite steep overhangs, which make it less glorious, and that's definitely a drawback.' (ID11, consumer product).

Repeatability is another major concern, which makes AM series production particularly challenging. Thus, designers are suggested to consider feature dimensions and tolerances carefully to compensate the uncertainty of dimensional deviations as a result of poor process repeatability.

'The repeatability can be quite sketchy so you make alterations according to first offs but then the next batch have a completely new issue. It's difficult to know what to change from the design perspective to improve this.' (ID04, engineering device).

In terms of mechanical properties, plastic AM parts are usually fragile along with the layer lamination due to relatively weak adhesion. Features are generally designed to be thicker than usual and proper build orientations should be specified in order to enhance strength. There are also many unknown mechanical properties such as fatigue, and thus AM is currently not considered to be a viable method for producing safety critical components that will be subject to frequent and cyclic loads.

8 AM DESIGN GUIDELINES AND RULES

AM design guidelines and rules are used to assist designers to effectively design the product for the chosen manufacturing process. The authors consider these guidelines and rules as three interconnected categories: (i) high level general guidelines mostly applied to conceptual design; (ii) feature level rules and (iii) printing rules typically applied to embodiment and detail design stages.

8.1 High level general design guidelines

In conceptual design, designers need to stand on a high level to conceive of the product whilst taking advantages of AM without going into detail (feature level). When starting a new design, designers first need to consider product application and function, followed by material, accuracy and surface finish requirements. Some interviewees also pointed out that the production volume might increase in the future if the product is successful or the client wants to switch to a traditional manufacturing method. In these cases, it is suggested to design the product to be compatible with a traditional process.

'So that's actually worth bearing in mind when you are designing it that you be able to take a step back into traditional manufacturing if it becomes necessary.' (ID07, consumer product).

8.2 Feature level design rules and 3D printing rules

Consistent with the findings from the literature review identified in Section 2, the vast majority of the design rules that are adopted in practical design work are detail design rules and 3D printing rules, which are used to refine the design and ensure the manufacturability of the features. Given that the aim of this paper is to develop a DfAM framework and investigate the implications of AM on design practice rather than introducing detail design rules, this subsection only outlines some typical rules.

Feature level rules are largely concerned with wall thicknesses, printable feature sizes, fillet radius, hole diameters, support structures in relation to surface finish, wear characteristics, clearances and tolerances. In addition, a significant difference between AM and traditional processes design rules is dimensioning. When designing for AM, designers will need to explicitly specify the following: build orientation, layer thickness, support structure and removal, machining method for post-processing and inspection procedures. This is because, for example, using different orientations, layer thicknesses and support structures will lead to varying part strengths, accuracies and surface finish etc.

3D printing rules are referred to as the rules used in the actual printing process. For example, how to lay out parts in a build chamber to achieve better and consistent part quality and to reduce cost. In SLS, the temperature of the centre of the bed is higher than that of the margins of the bed, which results in different degrees of distortion if a part is printed in the centre or close to the margin. At this stage, it is not clear how much designers should be expected to know about these printing parameters. Appropriate infill patterns can be used to reduce weight and printing time, but also impact on precision. Designers should also be aware of the build chamber size and the X, Y and Z accuracies of the AM machine to be used. This is because the machine accuracies in the X and Y directions are usually different from the Z directions, which requires fine tuning on the tolerances and allowances.

9   WIDER IMPACT ON OTHER COMPONENTS OF THE PRODUCT

When designing a complicated product consisting of a large number of components, AM may only be appropriate or feasible for producing certain components of the product. This study explores the impact of the components designed for AM on other components of the product designed for a conventional process. Both positive and negative impacts are highlighted below. The positive influences basically result from the capability to combine parts and build pre-assembled components:

- Product becomes more compact and adjacent components are incorporated into one component.
- Product structure becomes simpler.
- The mass of the product can be reduced.

On the other hand, other components of the product might potentially need to be redesigned, leading to increased product development time and cost:

- Some components need to be redesigned due to the nature of AM such as clogging resulting from support structure.
- Additional time for testing redesigned components.
- Additional cost for tooling modifications and testing.

'There was another constraint with my project that I had to ensure other components within the product didn't need to be redesigned. This is due to testing requirements, due to the function of our instruments and the risk that you would need tool mods etc. which were added costs. The benefits from the AM redesign did not justify that kind of additional expense.' (ID04, engineering device).

10 DESIGNERS KNOWLEDGE ON DFAM

The understanding of overall AM processes is a must-have skill, as indicated by the interview results. Unlike other conventional processes, 'AM' represents a group of techniques with both similarities and distinctions. Therefore, a clear understanding of the differences of various types of AM (including benefits and limitations) and the impacts on the design in terms of complexity and production scale will significantly facilitate the product design process. Moreover, designers need to be aware of economic viability, for example, viable production volume and high post-processing cost for high quality products. Material properties is another important factor because the way that the printed materials perform is different from machined or pressed materials. More importantly, the material properties, in a large extent, can determine the product geometry and support structure.

'Because the one was wax support structure that can melt out, might be really good for making small intricate channels and sort of sieve components whatever or filters. ... The one using the epoxy resin or FDM say, would be very difficult again to pour out the support structure.' (ID10, medical device).

11 DISCUSSION: IMPACT OF AM ON DESIGN PROCESS AND PRODUCTION

In this study, a majority of the interviewees indicated that the use of AM has changed their design process and practice. Products are designed in a more efficient and cost effective way and components can be simplified and combined, eliminating the need for tooling and assembly, and consequently reducing lead time. The capability of producing complex geometries has created significant design freedoms, allowing designers to focus on concepts, functionality and the value of the part rather than constraining what features can be delivered due to conventional process limitations. Furthermore, due to no tooling commitment, the design can still be changed without causing a significant additional cost and a huge production delay even before it is progressed towards production.

'What you really need to do, I would say, okay can I look at the whole system and then incorporate this, this, this and this, which is why, when you look at the additive from the clean sheet design point of view, you can incorporate so many parts into it, and it makes a lot easier to justify yourself.' (ID03, consumer product).

Some interviewees have witnessed the gradual paradigm shift from using AM for prototyping to using AM for tooling and one-offs, and increasingly towards low volume production. On the other hand, they are also sceptical about the trend of product design for AM due to the limited product properties that AM can currently offer. This in turn means that designers must leverage the advantages of AM whilst addressing the process limitations.

While a majority of the interviewees were positive towards AM as a viable production method, the majority of them still considered AM to be practical only for customised high value products in niche application areas, for instance, hearing aids in medical applications, complex components in aerospace industry and clothing and jewelleries in fashion industry. This is primarily attributed to the ability to make complex shapes and lightweight products with a low cost and reduced lead time. The interview results also reveal the fact that, despite AM becoming increasingly popular, the era of AM as a mainstream series production method is yet to come. Barriers to the widespread adoption of AM are largely associated with limited process capability for mass production, including low quality consistency, low machine reliability, inferior or unknown material properties, long lead times and high cost, and high cost for machine maintenance and downtime. It is noted that some designers adopt the strategy where products are designed following IM rules, though they will initially be additively manufactured. This is partially because IM rules are readily available and highly reliable, and also designing for injection moulding allows the products to be produced by IM if production volume increases.

Evidence from these interviews suggests that it is unlikely that AM is going to be a universal technology and replace other existing manufacturing techniques. It seems more reasonable to expect AM to be part of the production line to assist or play an important part in making certain components of a product.

'Perhaps it might be part of the process of the production line. I can imagine… when I talked about how components fit with injection moulded parts, maybe things like that. Perhaps that will be the point in the process where actually 3D printing is used, which is for one specific thing rather than making the whole product, because of the complexity, because of the nature of it.' (ID10, medical device).

Designers have also shown concerns about the viability of using AM to make functional parts due to the uncertainties of part quality and mechanical properties. It is worth mentioning that the boundaries of process capability and application are continuously moving along with the technology advancement. This will continuously challenge the current design process and enable the revolution of production model in enterprises.

12 CONCLUSIONS AND FUTURE WORK

The rapid development of AM technologies means that expectations have been raised regarding AM as a mainstream series production method. However, due to its unique process characteristics and the way that products are formed, new design methods and practices need to be developed. This paper proposes a DfAM framework that is aimed at providing an overview of the factors and considerations that designers need to consider in both process selection and during the design process. The framework

consists of five major elements: process selection; design considerations for conceptual, embodiment and detail design; control factors for process selection and design process (including AM process characteristics, design guidelines and rules, and wider impact on other components of the product); designer's DfAM knowledge; and impact of AM on the design process. The framework was built based on the data collected from the interviews with professional designers and AM practitioners. New design freedoms, opportunities and constraints are rooted in AM capability (e.g. producing complex geometries and part consolidation) and process drawbacks (e.g. orientation issues and poor accuracy) as well as the resulting production cost and lead time. In order to effectively design high quality products for AM, designers need a detailed understanding of AM processes including the differences between various AM processes and their associated benefits and limitations. In addition to following design guidelines and rules, designers should also be aware of potential impact of the components designed for and made by AM on other components of the product, such as increased production cost.

Given the limited sample size i.e. 11 interviews and 20 example products, the framework by no means cover all the elements that are necessary for designing a successful product. Additionally, the authors noticed that the interviewees sometimes had problems recalling how a particular product was conceived and designed. Their accounts may be adversely influenced by the fidelity with which they recall prior events. Therefore, future work will focus on enriching the framework by conducting more interviews and focus groups with designers working in a various industrial sectors to discuss important elements in DfAM and implementing experiments to validate the framework.

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