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Investigation of design for additive manufacturing in professional design practice

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ABSTRACT

Additive Manufacturing (AM) technologies are widely adopted in design practice for prototyping. However, the extent to which practitioners are knowledgeable and experienced in designing components for series production using AM remains poorly understood. This study presents the results of an online survey aimed at uncovering this emerging design activity, with additional evidence provided by semi-structured interviews with 18 designers. One hundred ten practising designers responded. The majority of the respondents remain sceptical about the potential for AM as a process for series production, citing cost and technical capabilities as key barriers. Only 23 reported experience in designing components for series production using AM, with the majority of these designing parts to be produced from plastic. The survey revealed that these designers have developed their own 'design rules' based primarily on personal experience. These rules, however, tended to focus on ensuring 'printability' and did not provide support for taking advantage of the unique capabilities of AM processes. The designers tended to treat AM processes as a uniform set of production processes, and so the design rules they used were generic and not directed to the capabilities of specific AM processes.

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Design for additive manufacturing; design-for-X; design practice; design knowledge; rapid manufacture

Introduction

Additive Manufacturing (AM) creates objects in a layer-by-layer manner, enabling complex geometries to be produced (Gao et al. 2015). These technologies have been available to designers for more than 20 years and have become firmly established as a prototyping tool for facilitating and accelerating the design process (Sass and Oxman 2006). Nevertheless, it is increasingly apparent that the new design opportunities enabled by AM have latent benefits beyond just prototyping. With continued advancement, AM has now shown significant potential to become an economically viable series production method; particularly for low volume production of end-use products (Ahuja, Karg, and Schmidt 2014; Atzeni et al. 2010, 2014; Manteil and Elsey 2016; Wohlers 2015).

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However, despite AM being widely heralded as 'the next industrial revolution' (Markillie 2012), there are, in reality, significant barriers to be overcome for successful adoption of the technologies (Royal Academy of Engineering 2013; Wohlers 2015). Arguably the major limiting factor in the uptake of AM by designers is the lack of codified and available knowledge that ensures not only how to successfully design 'printable' components, but also supports the exploitation of AM capabilities (AM working group 2015; Industrial and Regional Valorization of FoF Additive Manufacturing Projects 2014; Laverne and Segonds 2014; Li, Wu, and Myant 2016; Manteil and Elsey 2016; Meisel and Williams 2015; Royal Academy of Engineering 2013; Schmelzle et al. 2015; Thomas 2009; Thompson et al. 2016). To exploit these capabilities, it is important that industrial designers, design engineers and manufacturing engineers understand the implications of AM processes and rethink the concept of design for manufacturing (DFM) accordingly (Ahuja, Karg, and Schmidt 2014). As with any conventional manufacturing process, it is not possible to design effective components unless the subtleties of the process are understood by the designer. This essentially requires Design for Additive Manufacturing (DfAM) knowledge to be developed, enabling the transition of AM from rapid prototyping to a mainstream production method (Adam and Zimmer 2015).

In the past five years, there has been rapid growth in the number of academic research publications examining DfAM. It is evident that this is an emerging and rapidly changing field and one in which concepts and ideas are still forming. What we know to date about DfAM is largely based on prescriptive studies, while there is a notable scarcity of research investigating actual design practice. To date, two studies have attempted to study DfAM in practice. A qualitative study by Dorrington, Bilbie, and Begum (2016) examined the barriers for the adoption of AM in Small and Medium Enterprises (SME). The study provided an overview of the key enablers, transition support tools and appropriate skill-base for supporting the adoption of AM. However, as a qualitative study, whilst providing some interesting insights, it was from a very small number of practitioners. Similarly, Spallek and Krause (2018) investigated engineers' knowledge of AM in the German-speaking area. The study focused on three main aspects: knowledge of AM, experience in using AM and attitudes towards AM for the production of end use components. The results showed that whilst many practitioners have knowledge about AM processes, there is little experience in using AM for series production of end use components. However, the study was limited to the German speaking area and provided little insight on the adoption of AM for end use applications in industrial / product design.

Thus, there is some emerging, but limited knowledge about the uptake of AM as a production process by designers. The knowledge that exists suggests that there is limited uptake, but is based on exceptionally small samples of designers. Little is known beyond this regarding the barriers and enablers to the use of AM for end-use components.

To address this gap in the knowledge, the primary aim of this study was to explore the practice of designing end use components for series production using AM. The work presented here provides one of the first investigations into how practising designers are tackling design for AM in industry. The work was specifically directed towards a broad view of design but with a focus on industrial and product design as opposed to: safety critical engineering (where designs are often highly constrained), structurally-integral parts (where mechanical properties are highly critical); arts and crafts (where designs are largely unconstrained) and are typically 'one-offs'; or medical implants (where designs are highly personalised one-offs). This study encompasses both metals and plastics, but the majority of respondents are designing plastic components manufactured by either selective laser sintering (SLS) and/or fused deposition modelling (FDM).

The paper begins by summarising current knowledge on DfAM and identifying the limitations of previous studies. This leads to a description of the data collection methods. The survey results are then summarised along with insights from interviews with designers. Finally, the principal findings of the survey are discussed, focusing on answering the research questions and indicating future research directions.

Design for additive manufacturing (DfAM)

Design for manufacturing (DFM) is the practice of designing products to reduce or minimise manufacturing difficulties and costs, focusing at a component level, to optimise a component for the chosen process. Design for Additive Manufacturing (DfAM) aims to take advantage of the unique capabilities of AM to (i) design and optimise components according to the functions of the product/component and the requirements of the selected AM process for production; and (ii) rethink, redesign and refine an existing product/component, utilising the characteristics of AM to improve the functionality (Hietikko 2014). Guidance on DfAM has typically encouraged designers to tailor their designs to utilise the advantages of AM in enabling complex geometries and reducing weight, whilst being aware of AM process limitations, to ensure the manufacturability or 'printability' of the component or product.

In the last two years, there have been three review papers seeking to explore this topic and collate findings in this emerging field (Gibson et al. 2015; Kumke, Watschke, and Vietor 2016; Yang and Zhao 2015).

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 systematic review of literature on DfAM. They proposed three categories of studies regarding DfAM: (i) manufacturing, (ii) assembly and (iii) performance. They also presented three categories of AM-related design methods: (i) general design guidelines, (ii) modified conventional design theories and methodologies for AM (Tomiyama et al. 2009) and (iii) Design for Additive Manufacturing. Finally, they proposed three design aids: (i) a generic design framework that integrated a set of functional-driven design activities; (ii) a method for simultaneously synthesising process knowledge and functional requirements; and (iii) an analytic model for supporting the design process. However, the focus of their analysis was mainly on the design and optimisation of structural or mechanical components. As such, their principal focus was the attainment of desired mechanical properties. They were not seeking to explore how designers might use AM processes for a wider variety of components, where mechanical properties are less critical and other characteristics such as aesthetics and cost might be more critical than ultimate mechanical performance.

Kumke, Watschke, and Vietor (2016) suggested two categories of DfAM guidance according to their main purpose and application, titled 'DfAM in the strict sense' and 'DfAM in the broad sense'. 'DfAM in the broad sense' were additional approaches not directly related to the design process itself such as selecting the appropriate AM process and/or part candidates. In contrast, 'DfAM in the strict sense' included 'AM design rules' to ensure parts will be 'producible' (or printable) as well as 'AM design potentials' for taking advantage of AM capabilities. They integrated the 'DfAM in the strict sense' approaches into a design process model based on VDI 2221 (Jänsch and Birkhofer 2006). The review highlighted the lack of an overall design framework for DfAM and enumerated further limitations regarding the limited validity of many design rules, their focus only on a single optimisation objective and the lack of methods aimed at fostering innovative design solutions. While the review provided a systematic and comprehensive state-of-the-art, the focus remained, as in previous studies, mainly concentrated on engineering design and prescriptive approaches.

As identified in the literature, there is as yet no consensus on the terminology regarding DfAM methodologies, methods and tools. Notably, almost all studies distinguish between two different types of design guidance: (Gibson, Rosen, and Stucker 2010; Hague, Campbell, and Dickens 2003; Kumke, Watschke, and Vietor 2016; Laverne et al. 2015; Yang and Zhao 2015).

The first type of DfAM guidance relates to the particular 'capabilities', 'opportunities' or 'potential' of AM and is typically qualitative in nature (Yang and Zhao 2015). Many papers report on technological advances in additive manufacturing on and reflect on the potential of these developments for designers (Hague, Campbell, and Dickens 2003). Some studies present specific design guidelines (Yang and Zhao 2015), and others focus on the unique AM capabilities (Gibson, Rosen, and Stucker 2010), AM design potentials (Kumke, Watschke, and Vietor 2016) and 'opportunistic DfAM' (Laverne et al. 2015). Studies describing the capabilities of AM are seeking to raise awareness and encourage designers to design in a different way. However, many of the ideas presented are highly generic or abstract (e.g. 'new design freedoms', or 'light weighting') and are difficult to apply in practice. More specific or tangible guidance tends to be highly prescriptive, suggesting the use of a particular methodology. For example, Rosen (2007), who proposed a biomimetic approach and Salonitis (2016) who proposed a framework based on an axiomatic design method.

The second type of DfAM guidance is typically quantitative in nature and is much more comparable to traditional DFM rules (Boothroyd, Dewhurst, and Knight 2010; Bralla 1998; Poli 2001). These rules focus on component features to ensure manufacturability by communicating the limits and constraints of AM. Different authors use a range of terminology, including: design rules (Yang and Zhao 2015), AM design rules (Kumke, Watschke, and Vietor 2016), 'restrictive DfAM' (Laverne et al. 2015) and design constraints (Hague, Campbell, and Dickens 2003). These rules tend to apply at the detail design stage, to refine or optimise individual geometric features and their dimensions according to the capability of the specific AM process to be used. For example, Adam and Zimmer (2015) and Kranz, Herzog, and Emmelmann (2015) defined a set of detailed rules identifying feature types in relation to their dimensions. Adam and Zimmer (2015) conducted a series of experiments in order to optimise the dimensions of geometrical features such as wall thickness, outer and inner edges, slot depth, width and length and overhang length. Similarly, Kranz, Herzog, and Emmelmann (2015) explored detail design guidelines covering a wide range of prismatic features such as cavity, cylinder, wall and bore. Collectively, these feature level rules will indeed help designers ensure 'printability' (successful AM production) of parts, but they will not be helpful in ensuring the part being designed is conceptually optimal compared to alternative designs.

Limitations in current knowledge

These studies indicate that there is ongoing (and growing) scientific effort in investigating DfAM, but with some specific limitations.

Although significant efforts have been made in exploring design methods and rules for AM, arguably the majority of the research lies in developing detail design rules. Most of the rules are focused on checking and ensuring manufacturability (or 'printability') of designed features for specific AM processes. They are often based on extensive experimentation and thus have clearly demonstrated validity. However, they are less effective in providing insight into how designers might exploit the wider potential of AM. Tools such as topological optimisation, though utilising some unique AM advantages, are largely focused on mechanical requirements (e.g. strength and stiffness) neglecting others (e.g. maintenance and cleanability). However, there is also a need for guidance that might be appropriate at an early stage of the design process, when the design is not yet defined, and creative approaches could be adopted to generate innovative solutions that more cost-effectively exploit AM capabilities.

The majority of these design rules have emerged from individual case studies, or experimental approaches to evaluate the parameters of specific processes. What is not known is the extent to which practicing designers are aware of and are using this emerging body of knowledge regarding DfAM and the extent to which these rules or guidelines might be generalisable to different types of design practice.

Another limitation lies in the prescriptive nature of the proposed DfAM approaches. As Tomiyama (Tomiyama et al. 2009) suggests, prescriptive design methodologies find fewer applications in industrial contexts because they do not easily match the specific processes or approaches being used in industry. Such prescriptive processes might find some traction in firms (often larger firms) with more rigid procedures but are less compatible with the needs of smaller design teams. Again, this supports the need for more evidence on the adoption and use of different methodologies in professional design practice.

In conclusion, there is a clear and important gap in knowledge regarding the uptake of DfAM by designers practicing in industry. This is especially important in understanding the way in which designers use AM in their arsenal of available production processes. This paper specifically seeks to address this gap, to identify what is currently known by practicing designers and to what extent DfAM is being used in design practice and to what extent AM technologies are being adopted by designers as a potential manufacturing process for series production. For many designers, AM has secured its place in the design process as a tool for prototyping. However, if AM is to become more widely utilised as a process for series production, then it is essential that we understand the barriers and enablers of adoption. These might be barriers that require education, or indeed they might inform the next generation of machinery design to overcome technical limitations.

Methodology

To investigate current practice in designing end-use components for series production using AM this exploratory study has the following aims:

(a) Explore practising designers' experiences in designing series produced, end use components for AM.

(b) Understand the basis for selecting AM as a production process, along with the limitations of using it.
(c) Establish what, if any, DfAM knowledge has been used by designers, how it was retrieved and at which stage of the design process it has been used.
(d) Determine which stage of the design process is considered the most suitable for integrating DfAM knowledge.
(e) Understand the reasons why designers have not designed for AM.
(f) Understand what information and or knowledge practitioners require for designing end-use components in AM.
(g) Gather insights into how designers would prefer to access design knowledge for AM.

To achieve these aims, a mixed methodology was used, combining results from a survey of 110 designers and semi-structured interviews with 18 designers. Initially, a survey was the preferred approach, offering potential to gain insights from a large number of respondents. However, in analysing the results, it was evident that comparatively few had any significant experience in DfAM, especially for parts produced in production volumes. As a result, we followed the survey with more in-depth interviews, specifically targeting those designers with DfAM experience.

Survey

An on-line survey was initially selected as the best approach for gathering a large and plural viewpoint on current DfAM practice, trends and perceptions from the professional design community (Granello and Wheaton 2004; Wright 2005). We sought to collect evidence from a diverse and large number of practitioners and therefore provide a broad picture of current design practice. The survey targeted an audience of design practitioners, including practicing industrial, product and engineering designers.

The development of the survey instrument and the key decisions regarding the distribution involved four steps, prior to administering the full survey:

I. brainstorming relevant questions which uncover the aims of the study;
II. refining and organising the questions into a structured questionnaire for data collection;
III. designing and implementing an online pilot survey approach;
IV. modifying the survey approach and questionnaire in response to lessons learned from the pilot.

Both open-ended and closed questions were used, along with sets of closed answers for the closed questions. A routing system was also considered to screen participants with relevant experience in DfAM and direct them to more specific questions. The draft questionnaire was implemented on the on-line survey platform BOS (https://www.onlinesurveys.ac.uk/). The online survey platform allowed a rapid and inexpensive distribution of the survey and the implementation of an automatic routing structure. The BOS platform was configured to require respondents to answer all the questions and to indicate whether they wished to receive further information and/or participate in a follow-up in-depth interview. The questionnaire was then piloted in one of the academic institutions using a group of nineteen

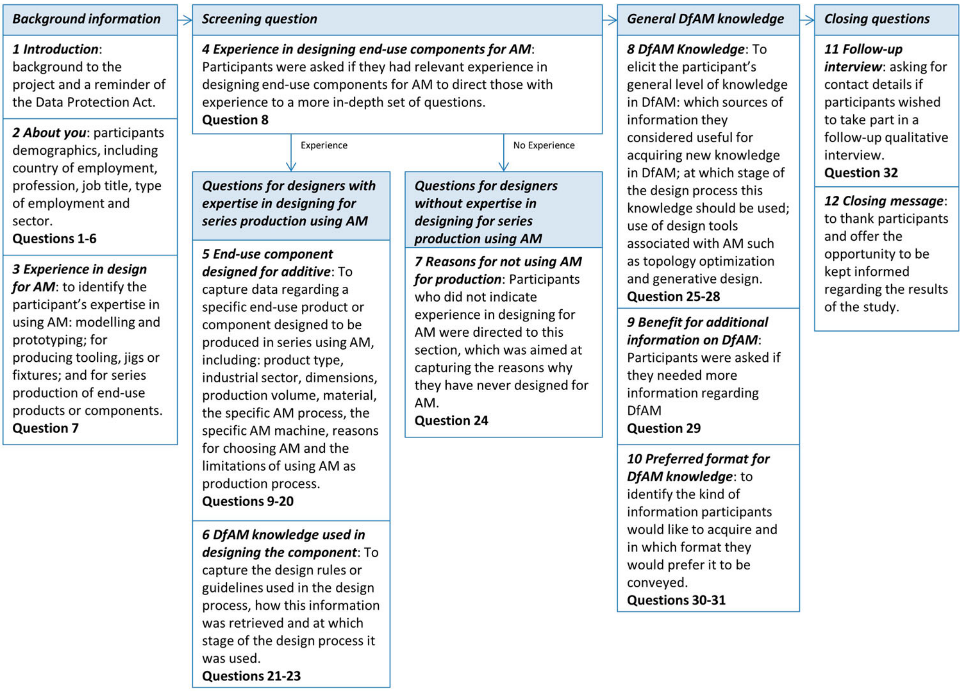

Figure 1. Structure of the survey.

people with relevant experience in DfAM (academic staff, post graduate research students and research associates). The responses from the pilot indicated the need for small modifications including detailed descriptions of each AM process and notes of clarification for some specific questions to reduce misinterpretations. The final survey was distributed to potential participants and comprised of twelve sections as illustrated in Figure 1 or the full survey is reproduced in the Appendix of this paper.

Sampling and distribution strategy

It was not possible to sample the whole design community randomly, as there are no readily available databases of designers with contact details. Therefore, a non-probabilistic convenience sample, although not representative of all designers, was considered as the most appropriate way to recruit participants. This was justified, as the aim of the study was to explore current practice, rather than test a potential hypothesis surrounding the topic.

To ensure a large and heterogonous number of participants with relevant experience in design were recruited, the survey was actively distributed online through different means:

(a) by emailing design practitioners retrieved through the websites, including: 'The directory of design consultants' (http://www.designdirectory.co.uk/ind.htm), 'Coroflot' (http://www.coroflot.com/) and Core77 (http://www.designdirectory.com/);
(b) by posting requests to various relevant Linked In groups, including: Industrial Design, Product Design, The Bureau of European Design Associations (BEDA), British Industrial

Design Association (BIDA), Industrial Designers Society of America (IDSA), Medical Devices Group, Design Thinking, 3D Printing, Medical AM & 3D Printing and Develop 3D;

(c) identifying potential participants via the newsletters of the website 3D Printing Industry and the British Industrial Design Association (BIDA).

(d) by private messages to existing contacts and LinkedIn members with a relevant background in product and industrial design.

A snowballing approach was also used, and participants were encouraged to refer the survey link to other potential participants.

The survey was launched on 31 May 2016 and the research team actively sought participants via the previously mentioned distribution modes until 30 July 2016. The online survey was then kept open, without any additional activity to recruit more participants, for one month further and continued to collect responses until it was closed on 31 August 2016.

Approach to analysis

Data from the closed questions were analysed using descriptive statistics (using statistical software SPSS version 23). Additionally, an index obtained by multiplying the value of the answers (e.g. 1 = 'Never', 2 = 'Seldom' 3 = 'Sometimes' 4 = 'Very often' 5 = 'Always') by the frequency of the respondents was used to summarise the Likert scale data (Matell and Jacoby 1971). For the open-ended questions content analysis and an inductive coding were performed with software (NVivo version 10 for Windows). Inductive coding was chosen because it allowed the categories to emerge from the responses while at the same time reflecting their variety and richness. Since the majority of the open-ended answers were simply enumerations of keywords without additional explanation, e.g. 'accuracy', 'cost', 'material performance', etc.; these keywords formed an evident foundation for recognising and naming the categories. The natural language of text was preferred for naming the categories, as opposed to more abstract terms from the design theory and the literature, since it acknowledged the original wording of the texts and the respondents' intentions.

Results from the survey

A total number of 730[1] visitors accessed the survey with 110 completing the entire questionnaire.

The majority of respondents had routine experience in using AM technologies for modelling and prototyping (Figure 2). Only a small minority had not used AM as a prototyping resource. Experience in using AM to produce tooling, jigs or fixtures was less widespread, but had been used by around 50% of the respondents. In contrast, a minority of respondents had used AM for the series production of components. Indeed, nearly 60% of respondents had never done this. This demonstrates that whilst prototyping with AM is now an established practice, these technologies have yet to gain widespread acceptance as a mainstream production process.

A screening question (Q8) asked explicitly whether participants had ever designed end-use products or components produced in AM. The results of this question confirmed that only a minority of our sample had experience in designing end-use components for AM

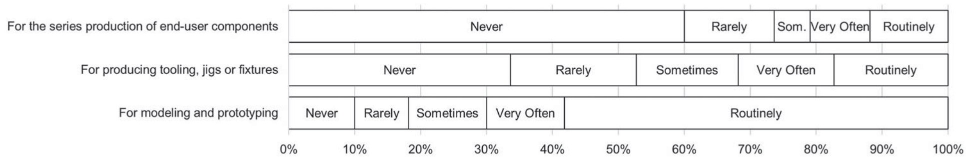

Figure 2. Experience of DfAM of participants.

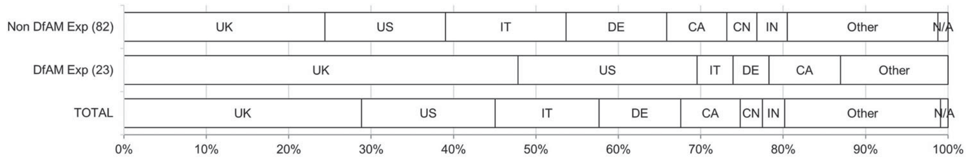

Figure 3. Nationalities of respondents.

(25%, $n = 28$ stating 'Yes' and 74%, $n = 82$ stating 'No'). Participants who answered 'Yes' and indicated they had experience in designing end-use components for series production in AM, were directed to sections 5 and 6 to explore their experience and knowledge in more detail. Although 28 respondents reported that they had designed end-use components for production using AM, three were excluded from the analysis because they provided incomplete answers while two were excluded because they provided an example of AM for prototyping and an example of AM for tooling. Responses from the remaining 23 (21%) participants are analysed later in this paper.

Hence for questions 5 and 6, we thus have a small number of respondents who have experience in using AM for series production. Whilst our ability to generalise for these questions is thus limited, we believe this to be a sample which is representative of the leading practitioners in this domain. Careful use of snowball sampling as well as existing contacts from project members and project partners helped to identify those practitioners with specific expertise. This low response rate indeed reflects the reality that most designers consider AM primarily as a prototyping tool. Indeed, it is possible that our sampling strategy may result in an over-estimation of the number of designers with experience of AM for series production.

In total, respondents from 25 countries participated in the study with the breakdown of nationalities shown in Figure 3. Whilst a majority of the whole sample was based in the UK, USA and EU, nearly 70% of respondents with experience in using AM for series manufacture were from the UK and US.

Most respondents defined their role as either 'Product Designer', 'Industrial Designer', or 'Design Engineer' (Figure 4). There is little discernible difference between the professions of respondents with or without experience in using AM as a production technology. An open text question also asked for the participants' job title, which confirmed the categories above, but also revealed that 31 respondents also have a managerial (e.g. director, manager) role (Figure 5).

Nearly 50% of the whole sample had between 1 and 5 years of experience (Figure 6). However, respondents with experience in using AM for production generally had

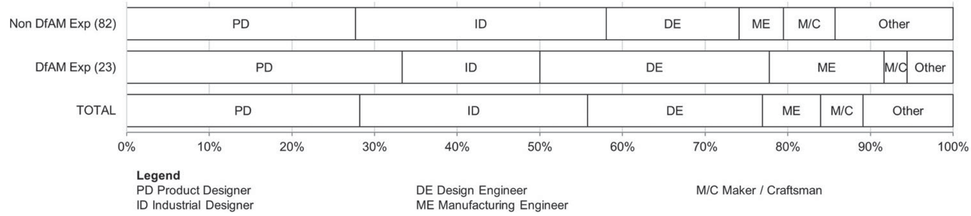

Figure 4. Profession of respondents.

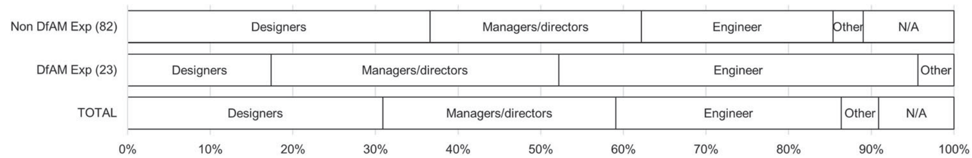

Figure 5. Job title.

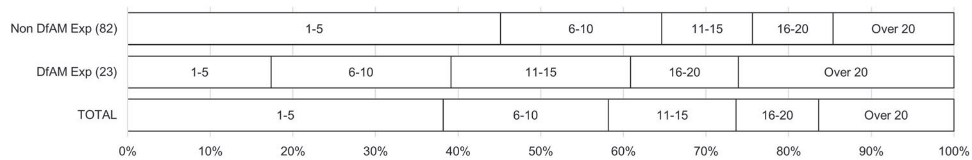

Figure 6. Design experience of respondents.

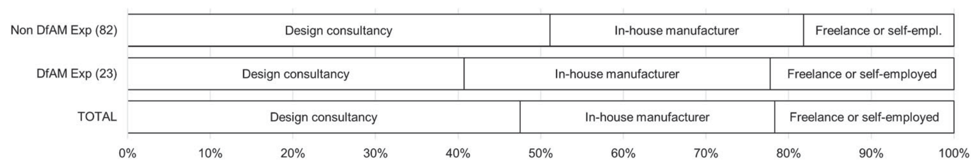

Figure 7. Employment of respondents.

more experience, with less than 20% of these respondents having less than five years of experience.

Nearly half of the participants indicated they are employed by design consultancies and roughly a third by in-house manufacturers, with little difference in these ratios between designers with and without experience in using AM for production (Figure 7).

Respondents indicated they had worked in 124 industrial sectors (Figure 8). The largest sectors for all respondents were consumer goods and healthcare equipment. However, designers working in healthcare sectors were more likely to have experience in using AM as a production technology.

Reasons for not using AM

The 82 participants who reported to have never designed for AM were directed to Question 28, which inquired about their reasons for having never designed end-use components for

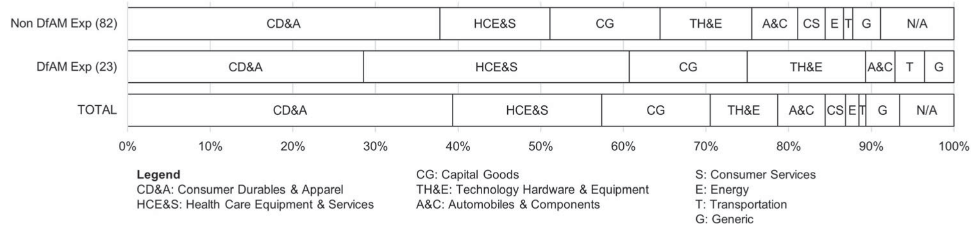

Figure 8. Industrial sectors of respondents.

series production in AM. This question uncovered 29 factors for not using AM for series production (Table 1). More than a third of these participants ($n = 31$) indicated 'cost' as their primary concern. Eight respondents indicated that AM 'has never been required' in their professional career. Other key reasons related to perceived limitations in the physical characteristics of printed parts, such as material performance, finish, accuracy and quality. Some cited concerns regarding the reliability and speed of the manufacturing process. Lack of knowledge was listed by surprisingly few ($n = 4$) suggesting concerns over technical capabilities outweigh a lack of knowledge regarding these processes.

Designers with experience in using AM for series production

This section reports on the responses from the 23 designers who self-identified as having experience in using AM for series production.

Component characteristics

Table 2 summarises the 23 components described by the designers with experience in using AM for production. There are eight sectors represented, with the largest being 'Consumer goods' and 'Medical devices'. We analysed responses to determine patterns in component size, material, production volumes and production technology:

- **Component size**: Respondents provided the overall dimensions of the component. The dimensions in the Z-axis (Mean = 63.5, Min = 8, Max = 280, Median = 50, Mode = 15, StDev = 66.7) are roughly half the size of those in the X-axis (Mean = 144.3, Min = 16, Max = 400, Median = 125, Mode = 200, StDev = 102.3) or the Y-axis (Mean = 116.3, Min = 10, Max = 500, Median = 70, Mode = 50, StDev = 123.7). A *T*-test was performed to explore the differences between the means of these dimensions. The results indicate a statistically significant difference between the dimensions in the Z-axis and those on the X-axis ($n = 23$ $t = 3.73, p \leq 0.05$) and Y axes ($n = 23, t = -2.41, p \leq 0.05$); a strong direct correlation between the dimensions of the X and Y axes, Pearson correlation = 0.76, $p \leq 0.05$ (2-sided *p* value); and an intermediated direct correlation between the dimensions of the Y and Z axes, Pearson correlation = 0.53, $p \leq 0.05$ (2-sided *p* value).
- **Production volume**: 5 participants indicated a total production volume of fewer than 10 pieces and 2 participants indicated a production volume between 1001 and 10,000. 8 participants indicated a production volume of between 11 and 100 units per annum,

Table 1. Reasons for not using AM for end-use components ($n = 132$ Reasons/$n = 82$ respondents).

Category	Example comments from respondents	No.	% of respondents ($n = 82$)
'Cost'	'Cost too high', 'economic requirements' and 'Metal parts can be expensive'	32	38%
'I do not design for series'	'I never design for series production', 'My objective to teach 3D tech, not to make stuff, per se.' and 'Private user. Most designs are for my own use or other individuals',	11	13%
'Has never been required'	'Has never been required', 'It has never been requested to me', 'Never thought' and 'Didn't happen'	9	10%
'Mechanical properties'	'The process often does not support either structural', 'poor mechanical properties of available plastics' and 'in some case because of mechanical properties'	8	10%
'Speed'	'Not fast enough', 'too long to produce an object' and 'Slow process'	8	10%
'Surface finishing'	'poor surface finish', 'Surface finish' and 'Typically gives a poor surface finish'	7	9%
'Production Volume'	'We often design relative high volume products (1000's to 1000,000's) and additive parts are more economical if made with traditional moulding', 'Prohibitive Cost and volumes' and 'At the current state might be good for a small production amount, but not for large volumes.'	7	9%
'Clients'	'Hasn't been an effective solution to client requirements', 'The process is not suited for my clients' needs', and 'The clients we work with do large production volumes that are typically manufactured in factories. Some have had parts CNC milled, but I haven't worked on any that have used additive yet.'	6	7%
'Material performance'	'Materials Performance', 'As it was not representing real material behaviour (stiffness, durability e.g.) of moulded plastic', 'Makes no sense because of time, price and material properties of product (project goal)'and 'As a company we do, however, on the parts that I would consider myself the designer, it was generally due to cost (linked to size & quantity) and/or materials which meant we went for different manufacturing methods.'	5	6%
'Accuracy'	'The process often does not support either structural, size/location tolerance', 'Dimensional inconsistency', 'inaccurate (tolerancing)'and 'The accuracy of making products'	5	6%
'Quality'	'Printers are not high enough quality', 'The fidelity is not always great – flash, lines, etc.' and 'Quality and appearance concerns generally, despite the short term and long term cost advantages.'	4	5%
'Reliability'	'seems not reliable', 'Dimensional inconsistency', and 'Process proved not to be as controlled as machining'	4	5%
'Lack of knowledge'	'Lack of knowledge/awareness on the part of the customer', 'The term AM is completely new to me, don't know anything about that.' and 'not familiar with the process.'	4	5%
'Accessibility'	'I do not have access to those process capable machines', 'No in-house machinery available' and 'The AM method haven't ben implied to our company yet. But at the moment a group of engineers including me are working on AM technologies'	3	4%
'Aesthetics'	'Aesthetic' and 'Quality and appearance concerns generally, despite the short term and long term cost advantages.'	2	2%
'Durability'	'Perceived lack of durability of the component' and 'Durability'	2	2%
'Limited available materials'	'limited materials selection' and 'limitation in material choice'	2	7%
'Complexity of the AM process'	'Complexity' and 'It seems like the current technologies is still sufficient and AM process need to be simpler.'	2	2%
'Chemical and environmental stability'	'Poor chemical and environmental stability of available thermoplastics and resins'	1	1%
'Not ready for series production'	'seems not reliable and ready for series production'	1	1%
'Post processing'	'finishing is required'	1	1%
'Resources efficiency'	'Currently, it is not a cost or resource-effective manufacturing process.'	1	1%

(*continued*)

Table 1. Continued.

Category	Example comments from respondents	No.	% of respondents (n = 82)
'Limitations for customized production'	'There is too much limitation for customize production as well.'	1	1%
'Standards'	'Not recognize by standard organization (CSA, UL, CE, etc.)'	1	1%
'Size'	'Mainly because of the cost or limitations in size'	1	1%
'Technical support'	'The limitations of technical support'	1	1%
'Supplier availability'	'supplier availability (most being interested in higher value prototype work)'	1	1%
'Requirements'	'When considering production quantities and requirements there are far better solutions',	1	1%
'Perception'	'Still viewed as a prototyping process'	1	1%

and a further 8 of volumes between 101 and 1000. None of the respondents reported a total production volume above 10,001 pieces. A *T*-test was performed to explore the mean difference of the dimensions between different production volumes and then the correlation between the size of the components and their production volume. However, the results showed only weak correlations between the variables with no statistical significance.

- **Material**: 'Plastic' was the material family used by the large majority of our sample (n = 21) with only two reporting 'Metal' (n = 2). More specifically, the plastics included Polyamide (n = 6), ABS (n = 4), Polyurethane (n = 1), Epoxy resin (n = 1) and PLA (n = 1). For the metals, one participant specified 'stainless steel' and roughly a quarter (n = 7) did not specify the metal used.
- **AM technologies**: With the exception of 'Sheet lamination', all seven categories of AM technologies were mentioned. The most commonly used AM technologies were 'Material Extrusion' (n = 6) and 'Powder Bed Fusion' (n = 7), accounting for roughly a third of the answers each. 'VAT photo-polymerization' was indicated by 4 participants and Material Jetting by 3. Over half of those surveyed (n = 16) mentioned the commercial name of the machine used for production. Inside this group, a large majority (n = 15) specified the name of a professional standard 3D printing machine with only one indicating a so-called 'desktop machine'. This indicates that despite the growth in popularity of desktop technologies, they are not yet sufficiently capable to be used reliably for production components.

Reasons for using AM

Respondents were asked to indicate the reasons why AM was appropriate. The majority (n = 20) of respondents provided reasons and a further four respondents also provided reasons for choosing a specific AM technology instead of another (Table 3). The dominant reasons were 'Low (production) Volumes' (n = 6), 'Complex shape' (n = 5), 'Speed' (n = 5), 'Cost' (n = 5), 'Shape manufacturability' (n = 4) and 'Customization' (n = 3). 14 other reasons were mentioned only once or twice.

Seven reasons emerged for choosing a specific AM technology instead of another with resolution (n = 2), reliability (n = 2) and the ability to process a specific material (n = 2)

Table 2. Characteristics of the components produced in series with AM.

Component	Product	Industrial sector category	Overall dimension (X, Y and Z; mm)	Production volume	Material	Process
'Handle'	'Aircraft'	'Aerospace'	100, 50, 50	1–10	ABS	VAT photopolymerization*
'Car driving performance tracker'	'We designed the casing'	'Automotive'	16, 10, 12	101–1000	'It's a composite of many materials'	VAT photopolymerization
'Electronic enclosure component'	'Interior Ribbing/battery holder'	'Consumer electronics'	30, 30, 8	101–1000	ABS	Material Extrusion
'Tonearm structure'	'Precision turntable'	'Consumer electronics'	300, 50, 50	1–10	Plastic	VAT photopolymerization
'Wristband with embedded tech.'	'Wristband + chipset+ AM tag'	'Consumer electronics'	195, 50, 15	11–100	Polyurethane rubber	Material Jetting
'A closet coat rack component'	'Rubbermaid Closet systems'	'Consumer goods'	54, 24, 15	11–100	Plastic	Material Extrusion
'Guitars'	NA	'Consumer goods'	400, 500, 45	11–100	Polyamide 2200	Powder Bed Fusion
'Home accessories'	NA	'Consumer goods'	70, 70, 100	1–10	polyamide powder	Direct Energy Deposition*
'Light diffuser'	'Table top lamp body'	'Consumer goods'	350, 350, 230	1001–10000	SLS polymer, can't remember the name	Powder Bed Fusion
'Transportation system for skis'	NA	'Consumer goods'	40, 80, 60	11–100	PLA	Material Extrusion
'Component'	'Thermal cover'	'Generic'	100, 10, 15	11–100	ABS	Material Extrusion
'Mounting bracket'	'Mounting bracket to hold routers to cruise ship walls'	'Generic'	120, 20, 60	101–1000	Plastic	Material Extrusion
'Mounting fixture'	NA	'Generic'	125, 125, 50	101–1000	Epoxy	VAT photopolymerization
'Filter/basket'	'A coffee measurement hopper'	'Industrial goods'	50, 50, 30	11–100	Stainless steel	Powder Bed Fusion
'Vacuum gripper'	'Handling machine'	'Industrial goods'	200, 200, 50	101–1000	Plastic	Material jetting
'A custom fit element for Normal earphones'	'Normal Ears (custom earphones) nrml.com'	'Medical device'	20, 10, 15	1001–10000	ABS printed on a Stratasys	Material Extrusion
'Component'	'Medical device'	'Medical device'	120, 280, 280	101–1000	ABS analogue	VAT photopolymerization
'Handpiece'	NA	'Medical device'	200, 200, 100	11–100	Plastic	Material jetting
'Patient specific implants, guides and prostheses'	'The human body'	'Medical device'	200, 200, 40	1–10	Metal	Powder Bed Fusion
'Customised foot orthotic'	'One part construction – no assembly'	'Medical device'	160, 90, 35	1–10	Nylon 11	Powder Bed Fusion
'Eye and face protection'	'Goggles'	'Safety equipment'	152, 50, 101	101–1000	Nylon 11	Powder Bed Fusion
'Air duct'	'Dry cell for laser diffraction instrument'	'Scientific instruments'	189, 140, 40	11–100	'PA'	Powder Bed Fusion
'Labware'	'Robot stage'	'Scientific instruments'	127, 85, 60	101–1000	Nylon	Material Extrusion

* Since the material-technology combination of this answer is not currently possible, we excluded material and process of this entry.

Table 3. Reasons for using AM as a production process ($n = 54$ reasons/$n = 23$ respondents).

Category	Example comments from respondents	Frequency
'Low Volumes'	'Short Run', 'We use this production technique for limited runs' and 'cheaper for small series production'	6
'Complex shape'	'Designs to (too) complex to manufacture otherwise', 'Complex shape required' and 'Geometric freedom to fabricate complex shapes'	5
'Speed'	'Speed', 'quick', 'Quick turnaround on iterations', 'Quicker and cheaper than tooling for moulding at this volume'	5
'Cost'	'Cheap costs', 'Cost' and 'Volume of production was cheaper than quoted tooling services'	5
'Shape manufacturability'	'Impossible to cast', 'Designs to (too) complex to manufacture otherwise' and 'There was a negative draft angle inside'	4
'Customization'	'Each guitar is customized for the user', 'Each part was custom designed and uniquely manufactured based on photos of customer's ears', and 'unique geometry'	3
'Part consolidation'	'We could do it in one single part' and 'Part could not be moulded in one piece'	2
'Easiness'	'Easy' and 'user friendly'	2
'Constant feedback'	'Having a constant feedback about the design' and 'Quick turnaround on iterations'	2
'Accessibility'	'Had access to printer' and 'In-house printer'	2
'Short development time'	'Less development time' and 'Fast turnaround project time scale'	2
'Lightweight'	'Lightweight'	1
'Internal Structure'	'Internal structure'	1
'Finishing'	'Finish met customer requirements'	1
'No stock'	'No need to keep ay bodies in stock'	1
'Before moving to CM'	'If successful a model would be cast and then moulded for wax injection'	1
'No need for aesthetic qualities'	'Hidden component, so aesthetics were unimportant'	1
'Confidentiality'	'Confidentiality'	1
'Precision'	'Precision'	1
'Organic shape'	'Organic form'	1
'No need for tooling'	'Avoidance of tooling hassle'	1
'Nano coating'	'Ability to use post coating of Nano crystalline copper'	1
'Low post processing'	'Low touch labour on post processing'	1
'Cryogenic performance'	'Cryogenic temperature performance'	1
'Optical properties'	'SLS provided a great light diffusing medium'	1
'Suitability for implants'	'Material and process suitability for medical implant applications'	1

being dominant. Other respondents noted the importance of access or availability ($n = 1$), low cost ($n = 1$), better part finishing ($n = 1$) and the lack of support structures ($n = 1$) as key reasons.

Perceived limitations of AM

Respondents report on the limitations they have faced when using AM as a production process (Table 4). The perceived high cost of AM in terms of build time and material is the most significant disincentive. Respondents also viewed post processing as a key limitation ($n = 4$). Respondents perceive limitations in the ability of AM technologies to produce parts with sufficient accuracy and repeatability ($n = 3$). Curiously, one participant also mentioned that (there are) 'No limitations if the product is optimised for additive'.

Design for AM knowledge

The majority of our sample ($n = 17$) reported to have followed specific design rules or guidelines for AM whilst designing components for series production, whilst six

Table 4. Main limitations for using AM as a production process ($n = 48$ limitations/$n = 24$ respondents).

Category	Subcategory	Example comments from respondents	Frequency
'Cost'		'Cost', 'Expensive', and 'Cost – reduced assembly significantly but still too expensive (though some issues with analysing 'true' costs of AM from business perspective)'	7
	'Cost of Materials'	'Cost of materials'	1
	'Cost due to build time'	'Price due to time in the machine'	1
'Post processing'		'Post production' and 'secondary processing required (soft touch paint)'	2
	'Labour for post finishing'	'Post finishing labour'	1
	'Long post processing'	'Lengthy finishing times'	1
'Productivity'		'Productivity of machines'	1
	'Production time'	'Lead time', 'time required' and 'Time to build'	3
'Materials'			
	'Mechanical properties'	'Need more, and stronger, materials' and 'Physical strength.'	2
	'Limited materials available'	'Need more, and stronger, materials'	1
	'Waste of material'	'waste of polymer powder'	1
'Build platform'			
	'Size of build platform'	'size of build envelope'	1
	'Orientation in the build platform'	'Deep understanding of the position of the product on the build platform'	1
'Accuracy'		'Tolerance', 'repeatability/stability of dimensions' and 'Accuracy of parts.'	3
'Surface finishing'		'surface finish' and 'Quality of finish'	2
'Quantities'		'Quantities.'	1
'Repeatability'		'repeatability'	1
'Incorporating threads'		'Limited ability to create critical hole features that incorporate threads'	1
'Flexibility'		'Flexibility'	1
'No limitations'		'none if the product is optimized for additive'	1

respondents did not answer this question. Table 5 provides a complete list of the design aids, guidance, rules or principles mentioned.

With few exceptions, there was a clear prevalence of detail design rules limited to ensuring 'printability' ($n = 10$), including rules relating to feature dimensions (e.g. minimum wall thickness) and component geometry (e.g. reduce layer cross section and avoid overhangs). Five respondents stated that they have utilised proprietary design rules without providing any additional information on the source or nature of these rules. Interestingly, 2 participants indicated that they utilised 'the same (rules) as injection moulding', specifying 'with different tolerances,' whilst one participant, in clear contrast indicated to 'ignore injection moulding design considerations'.

Two participants noted higher-level design principles, such as 'keep part simple' and 'component consolidation'. Two others specified printing guidance rather than design guidance, including determining the build orientation and incorporating structures to avoid stress build up during production.

Amongst the 28 respondents with experience of AM for series manufacture, their knowledge was mainly gained through personal experience, experimentation and discussion

Table 5. D4AM knowledge (24 respondents).

Category	Sub category	Example comments from respondents	Frequency
'Printability rules'			10
	'Clearance between parts'	'Left a gap based on resolution so parts fit together' and 'clearances between moving parts'	2
	'Avoid sudden changes in thickness'	'Avoiding sudden changes in material thickness'	1
	'Minimum distances between holes and edges'	'minimum distances between holes and edges'	1
	'Minimum feature size'	'Minimum feature size'	1
	'Minimum wall thickness'	'minimum wall thicknesses'	1
	'Strength across layers'	'Strength across build layers'	1
	'Avoid overhangs'	'avoiding overhangs'	1
	'Reduce layer cross section'	'Reducing layer cross sections.'	1
	'Rules for better surface quality'	'Rules to get better surface quality'	1
'Self-developed design guidance'		'My own', 'We ended up inventing our own guidelines as there weren't any.' and 'Proprietary'	5
'From conventional processes'			3
	'Same as Injection Moulding'	'The same of injection moulding but with different tolerance' and 'Normal plastic moulding plus discussions with vendor about material properties.'	2
	'Ignore injection moulding design considerations'	'ignored injection moulding design considerations'	1
'Design principles'			2
	'Keep part simple'	'Keep the part simple.'	1
	'Part consolidation'	'focused on consolidating components'	1
'Printing rules'			2
	'Incorporating structures to avoid stress build up during production'	'Incorporating structures to avoid stress build up during production.'	1
	'Build orientation'	'print direction'	1
Other			3
	'FEA'	'FEA.'	1
	'Collaborations with Engineers'	'Collaboration with engineers.'	1
	'Design rules for orthotics design'	'In-house design rules for orthotics design'	1
N/A			6

with experts (Table 6). Online sources, books and interrogation of prior designs were also used, with five respondents indicating they had attended training courses. The prevalence of experiential methods to develop knowledge is possibly indicative of the early stages of adoption of AM technologies as a viable production process, as this knowledge is yet to be formalised in a more systematically accessible way. We might speculate that because this knowledge has been gained by the designer's own experimentation and experience, they are therefore less willing to share this hard-learnt intellectual property. The protection of guidance that might be more widely utilised presents a genuine barrier to adoption of AM.

Timing of application of D4AM knowledge

The majority of our respondents stated that knowledge on DfAM is used at the detail design stage ($n = 18$), confirming insights gained earlier regarding the perception of this knowledge as enabling the printability of components. Ten respondents claimed to utilise

Table 6. List of sources used for gathering DfAM knowledge.

Category	Frequency
'Previous experience in AM'	14
'Experimenting with AM technologies'	13
'Speaking with experts'	12
'Looking at how products are made'	10
'Reading books'	7
'Surfing on the Internet'	7
'Attending a training course/s'	5
'Visiting trade fairs'	4
'Reading trade magazines'	2
'Other'	1

Table 7. Adoption of design aids at different design process stages.

Design stage	Frequency
'Brief setting'	7
'Conceptual design'	10
'Embodiment design'	11
'Detail design'	17
N/A	6

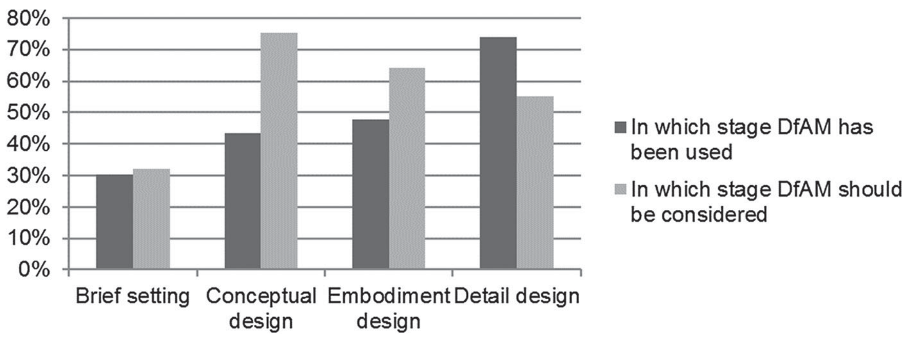

Figure 9. Comparison of DfAM adoption between design stages.

DfAM knowledge during conceptual design and six were not able to provide an answer (Table 7).

To understand the implications of these findings better, they were combined with responses to question Q27, which asked participants to indicate the stage of the design process at which DfAM knowledge should be considered. Q27 was open to all respondents, including those who did not have direct experience in designing parts for series production using AM. Because of the difference in the number of respondents between Q23 ($n = 28$) and Q27 ($n = 110$), percentages were used to compare the two results. Figure 8 shows that in practice, DfAM is mainly considered or used towards the detail design stage of the design process, although respondents acknowledge that these ideas should be considered earlier in the design process (Figure 9).

Table 8. Utilisation of topology optimisation and generative design tools.

Category	Not a tall	Slightly	Moderately	Very	Extremely	N/A
'Generative design'	52	13	23	13	6	3
'Topology optimization'	59	14	20	9	4	4

Utilisation of topology optimisation and generative design

The results from Table 8 shows that in product and industrial design practice 'Topology optimization' and 'Generative design' are not widely adopted. This is quite striking since AM is closely linked with these two computational tools. Several reasons can be speculated: the prohibitive cost for design consultancies of these software packages; a lack of knowledge of how these tools may benefit design practice; the focus on functions which are not strictly connected to product and industrial design (e.g. the attainment of high-end mechanical requirements; and a slow adoption rate.

Semi-structured interviews with designers

The survey responses indicated that very few designers had knowledge of DfAM and thus we were cautious about making any general claims as a result of their feedback. As a result, we also conducted interviews with relevant professional designers to explore designers' experience in designing end use products for AM production in greater depth.

As observed from the survey, finding designers with experience of DfAM was a significant challenge, as very few designers had actually designed products specifically for AM. Over the course of three months, 18 UK-based industrial designers were interviewed. They were identified using three sources: (i) partners of this research project; (ii) participants who completed the online survey and self-identified as having DfAM experience 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 (Table 9).

Eleven 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 min. 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 finally (iv) the designers' background. Each interview was centred on the discussion of one or more components or products that were specifically designed for production using AM, exploring the design considerations, rationale and limitations etc. 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 and categories were produced.

Table 9. Details of interviewees' positions, company and product discussed during the interview.

ID	Company	Position	Product	Date
ID01	A	Designer/ Researcher	Engineering device	21-06-2016
ID02	A	Designer/ Researcher	Engineering device	21-06-2016
ID03	B	CEO	Consumer product	19-07-2016
ID04	C	Industrial Designer	Consumer product	12-07-2016
ID05	D	Designer/ Researcher	Engineering device	04-07-2016
ID06	D	Design engineer	Engineering device	04-07-2016
ID07	E	Industrial Designer	Consumer product	06-07-2016
ID08	F	Product Designer	Engineering device	22-07-2016
ID09	G	Product Designer	Consumer product	02-08-2016
ID10	G	Designer/ Researcher	Medical device	02-08-2016
ID11	H	Industrial Designer	Consumer product	02-08-2016
ID12	I	CEO	Consumer product	09-08-2016
ID13	I	Design engineer	Consumer product	09-08-2016
ID14	I	Design engineer	Consumer product	09-08-2016
ID15	I	Design engineer	Consumer product	09-08-2016
ID16	L	CEO	Medical device	08-12-2016
ID17	L	Design engineer	Medical device	08-12-2016
ID18	L	Design engineer	Medical device	08-12-2016

We analysed results from the interviews in line with a generic design process, progressing from conceptual design through to detailed design and production. Relevant insights are described in the following sections and some selected quotations are included for illustration.

Issues in choosing AM as a production process

AM is well known for its ability 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. Interviewees were consistent in their view that one of the major drawbacks hindering widespread application of AM technologies for series production is poor process consistency, leading to printed parts having significant dimensional deviations.

Designers are aware of the potential for part optimisation to reduce component weight, but were concerned with the unknown durability of printed parts when they are repeatedly used and are exposed to direct daylight, high or low temperatures, humid environments, etc.

Interviewees indicated that they believed the viable production volume for AM is around 50 to 100 pieces (per annum), depending on component size. They noted that 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 or as a pre-cursor to investing in hard tooling post-launch.

Designers feel more comfortable selecting processes where there is reliable knowledge on the material properties. Such data exists for conventional processes (e.g. injection moulding (IM), machining and casting). In addition, extensive design rules are well-established. One designer noted:

> 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)

Issues in choosing one AM process over another AM process

AM represents a large family of layered manufacturing techniques that share some common features (e.g. building an object layer-by-layer), but each technique has its unique characteristics and drawbacks. Respondents noted a variety of reasons for selecting a specific AM process. Firstly, the capability of the process in terms of precision, surface finish, build size, feature size, printing speed, part strength and durability and the extent of post processing. A significant factor however is machine availability, with designers often choosing the process which is most convenient, rather than most suitable, particularly if they have specific AM machines in-house or at key suppliers. The final determinant of process choice was printing cost. Whilst designers acknowledged cost varies greatly between processes they lacked awareness of the actual costs. An indicative quote was given by one designer:

> 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)

Concept design and design rationale

Designers had two contradictory perspectives on how AM might be considered at the concept design stage. On one hand, some designers were adamant that to take advantage of AM, designers should not be constrained in their thinking. Specifically, they should not be constrained by the requirements of specific manufacturing processes. On the other hand, other designers strongly believed that some process-related factors need to be taken into account (e.g. the potential for part consolidation, ease of printing and assembly, mechanical and material properties, shape and size of each key feature, post-process cleaning of the material). However, most of the designers were in agreement that making design decisions at the concept design stage is challenging as there is a lack of effective guidance. As a result, they mostly rely on previous experience and tacit knowledge 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)

One of the main drivers for selecting AM as a production process was the designer’s need to create a shape that could not easily be manufactured using other processes as a result of integrating many components into a single part.

> 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)

A surprising observation from a number of designers was that they did not set out to design specifically with DfAM 'rules' in mind, but instead designed with a more conventional process guiding their decisions. They noted that especially where production volumes might grow significantly, the design is most effective if it is compatible with a higher volume process (e.g. injection moulding).

> 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)

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 (e.g. specific design rules to ensure printability of the designed part). Designers however noted specific concerns over availability of data on component precision and how to tolerance parts that are to be produced using AM, given the wide variation in quality between different processes and machines. In terms of printing quality, designers were also mindful of lamination effects and anisotropy.

> 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 empty space. (ID07, consumer product)

Perceived limitations of AM for series production

Although AM is often promoted as being able to provide significant design freedoms, designers described a number of perceived (or actual) limitations which reduce their likelihood of choosing AM.

Designers observed five specific process drawbacks: (i) orientation in relation to part quality; (ii) the need for substantial wall thickness; (iii) dimensional accuracy and surface finish; (iv) process repeatability; and (v) post-processing. Amongst these drawbacks, interviewees were most concerned about accuracy and surface finish. Process repeatability is the dominant concern of designers. Thus, AM might be most applicable where dimensional precision is not a significant factor. All designers felt that more information on dimensional repeatability would be beneficial. Many designers have experienced the need to modify the CAD model to reflect the actual build in order to accommodate shrinkage or dimensional imperfections. However, poor underlying process repeatability means that this is not always reliable.

> 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, designers perceive plastic AM parts as being fragile. To accommodate this, features might be designed to be thicker than usual and build orientation should be specified carefully 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 critical plastic components that will be subject to frequent and cyclic loads.

Knowledge of 'design rules' for AM

Consistent with the findings from the literature review and the survey, the majority of design rules that are adopted in practice focus on the optimisation of specific design features (e.g. overhangs, wall thicknesses, printable feature sizes, fillet radius, hole diameters, support structures in relation to surface finish, wear characteristics, clearances and tolerances). The interviewees had a reasonable knowledge of these rules, but not as a result of reading academic studies, but by a combination of word-of-mouth and their own experience.

Interviewees indicated that understanding the overall AM process is becoming a must-have skill for designers. 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 are another important factor because the way that the printed materials perform is different from machined or pressed materials. More importantly, the material properties, to 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)

Discussion

Experience in designing end use component in AM

The results presented above show that despite the hyperbole the excitement surrounding AM technologies, their use is mainly reserved for prototyping (Sass and Oxman 2006) and tooling (Chua, Leong, and Liu 2015; Dippenaar and Schreve 2013; Rahmati 2014; Rayegani et al. 2014).

Along with the findings of Dorrington, Bilbie, and Begum (2016) and Spallek and Krause (2018) our results demonstrate that a significant proportion of practitioners (c. 80%) have never designed end-use components for series production using AM technologies, despite having used AM for other purposes. Indeed, the proportion of designers with experience of using AM for production may be lower than identified in our sample, which risks a self-selection bias (Wright 2005) from designers who are already interested or knowledgeable in this domain. In fact, the number of people who did not complete the survey reinforces this hypothesis and provides an approximate indication of this effect. The language and the terminology adopted in the survey might also have impacted participation, as AM is possibly less widely recognised than the more common term '3D Printing'.

A very small set of practitioners seem to have designed end-use components for series production using AM. These designers had mainly gained their knowledge regarding the design rules and principles for AM as well as the limitations of these technologies as a result of personal experience. This experience is typically applied to the design of low to medium volume production components in sectors including consumer goods, electronic goods and medical devices. This suggests that, while most current research is focused on highly technical (safety critical) fields, there are also applications for series production using AM in industrial and product design. This seems to support the hypothesis that AM should be considered as a manufacturing choice for industrial, product and engineering designers providing there is sufficient design guidance to enable appropriate process selection based on functional and economic criteria.

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.

Although, there was great variation in the dimensions and proportions of the components produced in series using AM (from $20 \times 10 \times 15$ to $400 \times 500 \times 280$ mm, with a mean size of $144 \times 116 \times 64$ mm), as we anticipated, the median part size showed a significant favour for smaller parts probably due to the lengthy build times required for larger parts. In general, height in the Z-axis was approximately half of the size of the dimensions in the X and Y-axes. This may be explained by the heterogeneous nature of AM components where resolution, accuracy (Boschetto and Bottini 2016; Lee et al. 2014) and mechanical properties differ between the vertical and horizontal axes (Ahn et al. 2002; Leigh 2012). This variation is also explained by differences in production time and cost between the horizontal and vertical axes (Costabile et al. 2016). Due to significantly longer time required in adding layers in almost all processes, there is a significant incentive to reduce z-height where possible. A conclusion is that a typical component for AM has small to medium size with flat and wide proportions.

There have been some suggestions that AM for plastics can be suitable for production volumes up to tens of thousands (Atzeni et al. 2010; Hopkinson and Dickens 2003; Stucker 2011). However, in our survey, the production volumes indicated were typically between 11 and 1000, which is in agreement with the results reported by Karania and Kazmer (2007).

Production volume using AM processes has a relationship with component size, and previous studies (e.g. Atzeni et al. 2010; Hopkinson and Dickens 2003) have concluded that AM processes are more suitable to series production of small parts and found an indirect strong correlation between size and production volume. Surprisingly however, our survey did not reveal any significant statistical correlation between these two variables. This result is probably affected by the fact that the production volumes of the smaller components were generally lower than 1000 per annum, even if higher volumes were theoretically possible (Atzeni et al. 2010; Baumers et al. 2016; Hague, Mansour, and Saleh 2004; Stucker 2011). This could indicate that regardless of size, AM currently remains best suited to low volume production.

As expected, the predominance of polymers among our data can be explained by the industrial and product design target of the survey. The most common material and process combinations for end use components were Material Extrusion (e.g. FDM) with ABS and Powder Bed Fusion (e.g. SLS) with Polyamide. For material extrusion, ABS is comparatively low cost and provides good material properties, including greater potential for post-process finishing. For powder bed fusion, Polyamide has a relative low cost (a result of high build capacity), good accuracy, provides good resolution and good material properties (Ruffo, Tuck, and Hague 2007). Vat photopolymerisation is also being adopted for series production, although normally considered better suited to prototyping (e.g. Cotteleer 2014) due to the poor stability of mechanical properties over time and relatively high cost; a result of high cost of materials and low production speed (Hague, Mansour, and Saleh 2004; Kim and Oh 2008), despite offering very high resolution, accuracy and surface finish. A possible explanation could be the development of new materials that are better able to approximate the mechanical properties of engineering polymers (Huang, Weng, and Sun 2011; Jardini et al. 2006; Rubber 2003; Schuster et al. 2007; Zhang, Jin, and Zhao 2013).

Advantages and limitations of AM for series production

The main reasons for using AM provided by our participants are consistent with those identified in other studies, including 'low volumes', 'complex shapes', and 'customization' (Achillas et al. 2015; Lipson 2011; Ruffo, Tuck, and Hague 2006; Stucker 2011, Spallek and Krause 2017), offering advantages over traditional manufacturing processes (Baumers et al. 2016). What is surprising is that the other main reasons such as 'cost' and 'speed' are often considered limitations of AM rather than advantages (Bourell, Leu, and Rosen 2009; Hopkinson and Dickens 2003). This inconsistency may be related to other factors that are concurrently considered during process selection, for example production volume and shape complexity. If the production volume and the part size are low or the shape particularly complex to fabricate, AM becomes an economically viable alternative (Atzeni et al. 2010; Stucker 2011). Participants might have interpreted 'speed' in reference to the overall development process rather than the time required to produce the component(s). The production time of a component made with AM is generally much higher than the production time of the same component made with conventional processes (Baumers et al. 2016). However, if design, production and set-up time for the tooling required for a conventional process are considered, AM may provide the shortest time-to-market (e.g. Achillas et al. 2015; Ford 2014).

Perhaps the most interesting observations regarding the benefits of AM as a production process were those only noted a few times. Some of these observations are in line with conclusions from previous studies, including: 'Confidentiality', 'Constant feedback', 'Easiness', 'Short development time', 'Lightweight', 'No stock', 'Organic shape' and 'No need for tooling' (e.g. Dorrington, Bilbie, and Begum 2016; Stucker 2011). Other observations are more unusual, including 'Optical properties', 'Suitability for implants', 'No need for aesthetic qualities', 'Nano-coating' and 'Cryogenic performance'. These reasons are seldom cited in academic literature and they provide a glimpse of the diverse range of motivations that can lead to the selection of AM in industry.

'Cost' was the most strongly stated reason for not choosing AM for series production. This is interesting since it is both the main reason for choosing AM and the main limitation. To shed some light on this contradictory result, we compared the reasons for choosing AM of the designers who mentioned 'cost' as a limitation. We observe that despite AM being considered expensive on a per part basis, designers selected it because of its unique capabilities (e.g. producing complex shapes) that added value that more than compensated for the higher part cost. This might reflect that, although cost is a crucial factor for designers in materials and process selection, it is not necessarily the dominant driver in itself (Pedgley 2009). Designers may favour more expensive AM processes over conventional alternatives because they may be able deliver long term economic benefits (e.g. fuel savings in the aerospace sector due to lightweight components) or because they may provide some added value not achievable with conventional alternatives (e.g. personalisation of implants). Similarly, to 'speed', cost must also be considered in its entirety. Although per part cost for AM may be much higher, when tooling costs are factored in, the cost per component in a batch could be favourable.

As regards the other limitations, we noticed that by aggregating all the elements that broadly belong to a 'Build quality' category (i.e. mechanical properties, surface finish, material performance, accuracy, quality, reliability, durability, chemical and environmental stability and not ready for series production), this category would surpass 'Cost' with a total count of 36. This may indicate that a major limiting factor for the adoption of AM is that designers do not yet consider these processes truly mature for end use applications. For instance, AM techniques are widely regarded as processes that provide low surface quality and low dimensional accuracy compared to conventional processes (Boschetto and Bottini 2016; Lee et al. 2014; Thompson et al. 2016). Therefore, components made in AM often require laborious post-processing. This is consistent with observations from previous studies, alongside concerns over accuracy, surface finish and productivity (e.g. Baumers et al. 2016).

Finally, one limitation needs special consideration. One participant mentioned that there were 'none (no limitations) if the product is optimized for additive'. This single statement acknowledges the role DfAM knowledge as an enabler for exploiting AM capabilities.

This refined data set also highlights a general difficulty in attempting to produce generalised claims for AM, as there is a great variety of sub-processes and machines, each with different capabilities and limitations. Evidence from the qualitative interviews suggest 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.

Knowledge of design principles and design rules for AM

With few exceptions, the designers were generally most aware of what might be considered as 'detail design rules'. This prominence of detail design rules supports the notion that current DfAM knowledge is mainly limited to ensuring 'printability' in the late stages of the design process. Thus, designers might modify a component to ensure the correct wall thickness or reduce the size of an overhang. In so doing, these rules do not encourage designers to take a more holistic view to ensure that the component is not only printable, but also takes advantages of the specific capabilities of these processes (Guo and Leu 2013). There thus appears to be a missed opportunity in guidance that encourages an 'additive manufacturing mind-set' during concept design.

Another important finding was the dependence upon 'self-developed design guidance'' used for the design of the AM components. Over half of the participants noted the importance of previous experience, experimentation and looking at how (other) products are made. This can be explained in part by two concurring factors. First, it may confirm our assumption that there is a lack of readily available and trusted DfAM knowledge. This has been widely highlighted in recent studies (Li, Wu, and Myant 2016; Lindemann and Koch 2016; Thompson et al. 2016). A non-exclusive explanation could be that with easier access to low cost AM technology, it is easier for designers to self-learn design knowledge than it is with conventional manufacturing processes. Additionally, the low cost and speed of the AM process means that designers can iteratively perfect their design through prototyping and then apply that design directly to the production process. So with AM, designers can directly engage with the production process and shape the final outcome through prototyping that is identical to the final product (Karana, Pedgley, and Rognoli 2015). Thus, the concepts of 'product' considered as the final materialisation of the design intent and 'model' considered as a tool for design exploration and evaluation are no more distinct conceptual entities (Gursoy and Ozkar 2015), but they blend as in craftsmanship (Anderson 2010; Bettiol and Micelli 2014). However, this reliance on personal experience is inefficient and means that designers may not be aware of rules conceived independently by other designers.

A conflicting outcome also emerged between the adoption and rejection of injection moulding design guidelines (IMDG) when designing components for AM. Two participants of the survey declared that they followed the 'Same (design rules) as Injection Moulding' while another declared to 'Ignore injection moulding design considerations'. As our qualitative interviews confirmed, the former may view AM as a stepping-stone to injection moulding later. Interestingly, literature has generally supported the idea that to exploit AM capabilities for the production of end use components fully, design rules for conventional processes should be neglected (Hague, Mansour, and Saleh 2003, 2004). However, this contradiction might be evidence of the manufacturing-driven and function-driven design strategies proposed by Klahn, Leutenecker, and Meboldt (2015) and Leutenecker-Twelsiek, Klahn, and Meboldt (2015). As our qualitative interviews suggest, adopting IMDG can reduce the risks associated with the market introduction of new products. It may also be that designers already have experience designing with injection moulding in mind, but find that these designs are readily printable as prototypes. Injection moulding design rules (e.g. round corners to reduce stress concentrations or thin uniform wall thickness to reduce distortion) also apply for AM and so applying them could be considered 'safe'. As such, they may ensure parts are printable, but by following the design guidelines, the capabilities of AM might not be exploited fully. This contradiction requires further investigation to understand more in-depth when these two perspectives should be adopted.

One survey respondent agreed that the design principle 'keep part simple' applies to the design of AM components. However, this principle is in contrast with much of the literature on DfAM, which emphasises the possibility of making complex shapes (Ahuja, Karg, and Schmidt 2014; Boyard et al. 2014; Chryssolouris et al. 2012; Hague, Campbell, and Dickens 2003; Hague, Mansour, and Saleh 2003, 2004; Hopkinson, Hague, and Dickens 2006). An interpretation could be that, even when complex geometries are possible, they might not always be an appropriate solution since complexity might interfere with other design requirements, for instance cleanability or maintenance. Moreover, although AM can generate very complex shapes, conversely it can equally well fabricate simple geometries.

A survey respondent also agreed with the design principle 'part consolidation', which is advocated as the one of the main advantages of AM. For instance, part consolidation can be used to reduce assembly operations, decrease material consumption and improve reliability (Hague, Mansour, and Saleh 2004; Schmelzle et al. 2015; Tang, Yang, and Zhao 2016; Yang, Tang, and Zhao 2015; Yang and Zhao 2015).

The design rules 'build orientation' and 'incorporating structures to avoid stress build up during production' were also noted. Interestingly, these two rules can be interpreted as related to production rather than design. Whilst the impact of build orientation for AM components is widely recognised (Cooke et al. 2011; Urbanic and Hedrick 2015) it has only recently been recognised as an issue to consider in the design process instead of a decision to be made in production (Leutenecker-Twelsiek, Klahn, and Meboldt 2016). This highlights that in AM, design and production decisions are closely interrelated, and that the designer must also act as 'production engineer'.

The comparison between the design stages where DfAM is currently adopted and those where it should be adopted provided compelling results. Although DfAM is currently implemented in the detail design stage, the findings reveal that designers recognise DfAM should be considered much earlier in the design process to exploit AM capabilities fully. This confirms the conclusions of previous studies that highlighted the lack of DfAM knowledge and aids targeted at the conceptual design stage (Doubrovski, Verlinden, and Horvath 2012; Guo and Leu 2013; Laverne and Segonds 2014; Rias et al. 2016).

Although, our sample is comparatively small, these insights seem to demonstrate that the design knowledge surrounding AM in professional practice is still at an early stage of development. The prevalence of detail design rules, self-developed design guidance and contradictory statements are clear indications of this.

Reasons for having never designed end use components for series production in AM

Perceived high cost was the primary reason stated for not using AM amongst the participants who have not designed for AM. This was expected, and it is consistent with the experienced respondents and with the academic literature (Ford 2014, Spallek and Krause 2017). This further confirms that 'Cost' is the most relevant process selection criterion when dealing with AM. However, 'Cost' alone remains a contradictory result and other factors such as production volume and size need consideration. For example, if 'Cost' is the main factor for not using AM, this is probably due to the fact that most participants design components for higher production volumes than those suitable for AM (Baumers et al. 2016; Lindemann and Koch 2016); therefore, generally opting for other 'cheaper' processes.

Our sample also stated that AM has 'never been required' indicating that there may be inertia in the adoption of AM. This is consistent with a long tradition of research that has found the uptake of new technologies to be slow beyond a few innovators (Livshits and Macgee 2006; Rogers 1995).

Other reasons relate to the known technological limitations of AM and are consistent with the limitations identified by previous studies (Baumers et al. 2016; Boschetto and Bottini 2014; Boschetto, Giordano, and Veniali 2013; Dimitrov et al. 2014; Ford 2014; Gao et al. 2015; Huang et al. 2013; Oropallo and Piegl 2016). There are strong perceptions that AM processes are not repeatable, have poor surface finish and are generally not reliable. This might not be true for the 'high-end' machines, but the plethora of low-cost and low-performance machines might contribute to this view. Indeed, despite the large number of AM machines now available, the process itself might still be considered immature in comparison with established manufacturing methods. This maybe a serious limiting factor for the adoption of AM, since designers might be biased towards conventional processes.

There appears to be widespread awareness of the technical limitations of AM processes amongst designers whilst knowledge of the design rules or principles that might be deployed to overcome these limitations is more limited. Indeed, the sample acknowledges this knowledge deficiency as a key barrier for the selection of AM as a production process. There is a clear and evident need to improve the knowledge of designers and to develop better design tools and methodologies in order to improve the uptake of AM as a production process (AM working group 2015; Industrial and Regional Valorization of FoF Additive Manufacturing Projects 2014; Li, Wu, and Myant 2016; Manteil and Elsey 2016; Quarshie et al. 2012).

Some respondents' reasons for not using AM related primarily to their ability to access machinery, either directly or through suppliers. It has previously been identified that the choice of manufacturing processes by designers are often constrained (or directed) by convenience (e.g. Pedgley 2009) and not necessarily for technical or knowledge reasons. This might indicate that although AM could theoretically be recognised as the most suitable production solution, it requires a change in existing designers' practices.

We found little evidence in our survey for the existence (or not) of standards being an impediment to the selection of AM as a production process, although this has previously been noted as a key barrier (e.g. Ford 2014).

It is clear that a range of barriers is impeding the wider adoption of AM technologies for series production, including technological as well as behavioural factors. Future research efforts might give further attention to these behavioural aspects and particularly the practitioners and consumers' acceptance of AM.

Impact of AM on the design process

In our interviews, 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)

Conclusions and future work

In this paper, we have presented data from a survey examining the extent to which practising designers in industry are designing end use components for series production using AM. Amongst those with specific experience, we sought to understand the nature of the components being designed and the sources of the designers' knowledge regarding DfAM. For those with no experience, we sought to understand the barriers to selecting AM as a production process. Our main conclusions are summarised below:

- Designers continue to view AM as a tool that has greatest benefit in prototyping during product development. As a result, the design of components for series production in AM is rarely considered.
- In industrial / product design, plastic components designed for series production using plastic-based AM are generally produced in low volumes (typically less than 1000 pieces per annum) and are relatively small (typically no larger than $150 \times 150 \times 50$ mm). AM is mainly being applied for the design of consumer goods and medical devices.
- Designers develop their knowledge of how to design for AM largely based on personal experience. However, most of their insights are focused on ensuring 'printability' of the part, with limited evidence of the application of design rules that not only ensure printability, but that also mean the component takes advantage of the specific capabilities of AM processes.
- The barriers to adopting AM for series production are dominated by perceptions of high cost and in addition, designers are not yet convinced that AM technologies will deliver components that are dimensionally repeatable and have satisfactory physical properties.

It is interesting to note that respondents did not seek to make any great distinction between the different AM processes, treating all AM processes as a homogeneous group. In reality, these processes have very different properties. 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 small number of respondents with direct experience in designing for AM as a production technology ($n = 23$) and the limited sample size i.e. 18 interviewees, care needs to be taken in generalising these findings. 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.

This study data provides a clear description of current knowledge and practice amongst designers, but to gain deeper insights, future research should aim for larger sample sizes with a more in-depth focus on some of the single most important aspects that have emerged from this study. This is especially important given the low number of respondents with any depth of experience. With a sufficiently large number of responses, it would be possible to examine different approaches to AM, and especially how design practice for AM differs from these observations in metals-based AM processes employed in sectors such as aerospace, automotive and defence.

Note

1. This number indicates the number of times the survey was accessed. If one person has accessed the survey multiple times without completing it, this counted as a separate instance each time. Therefore, this number only provides an approximation of the number of people who accessed the survey and not the actual number.

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