Design for
Additive
Manufacturing

DESIGNING END USE COMPONENTS FOR ADDITIVE MANUFACTURING

Exploring experiences, knowledge and information requirements

AN ONLINE SURVEY OF PRODUCT AND INDUSTRIAL DESIGN PRACTITIONERS

UNIVERSITY OF CAMBRIDGE
Loughborough University
EPSRC
IfM MANAGEMENT TECHNOLOGY POLICY

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Contents

Executive Summary

The primary aim of this study was to develop an understanding of the experience, the current knowledge regarding the design of end-user components for series production in additive manufacturing (AM) and the information needs of designers involved in designing end-user components for AM. To achieve this, the survey intended to uncover the following aspects of the topic:

1. If and how frequently AM technologies are used by designers for series production of end-user components
2. To what extend designers have had experience of designing end-user components for AM
3. Which aspects are important when designing end-user components for additive
4. Why designers have or not have designed end-user components for series production in AM
5. How designers have learned how to design for AM and which resources they have used
6. What designers would like to know about Design for AM
7. How they prefer this information to be conveyed

Introduction

Additive Manufacturing (AM), also referred to as 3D Printing, is revolutionising the way products are designed and manufactured. AM creates objects in a layer-by-layer manner, enabling complex geometries to be produced (Gao et al. 2015). These technologies have been available to designers for more than 20 years and have become firmly established as a prototyping tool; 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 (Wohlers 2015; Manteil and Elsey 2016; Ahuja, Karg, and Schmidt 2015; Eleonora Atzeni et al. 2010; E Atzeni et al. 2014).

However, despite AM being widely heralded as *'the next industrial revolution'* (Paul Markillie 2012) there are, in reality, significant barriers to 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 (Industrial and Regional Valorization of FoF Additive Manufacturing Projects 2014; AM working group 2015; Royal Academy of Engineering 2013; Li, Wu, and Myant 2016; Manteil and Elsey 2016; Thompson et al. 2016; Meisel and Williams 2015; J. Schmelzle et al. 2015; Thomas 2009; Laverne and Segonds 2014).

To exploit AM capabilities, it is important that designers, engineers and manufacturers understand the implications of AM processes and accordingly rethink the concept of design for manufacturing (DFM) (Ahuja, et al., 2015). As with any conventional process, it is not possible to design effective components unless the subtleties of the manufacturing 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 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. Moreover, what we know to date about DfAM is largely based on prescriptive studies, while there is a notable paucity of research investigating actual design practice.

To address this gap in the understanding of DfAM, the primary aim of this study was to explore the practice of designing end-use components for series production using AM, which is so far little discussed in the literature. 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 highly constrained), arts and crafts (where designs are largely unconstrained) or medical implants (where designs are highly personalized one-offs).

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

Method

Survey

An on-line survey was the most efficient way of gathering a wide perspective of the topic from professional designers in industry.

The language of the survey was English in order to reach a wide international audience without the need for localisation. The language of the survey was crosschecked by two English native speakers and by two non-native English speakers verifying that the meaning of the questions could be understood by speakers of English as a first and second language.

The development and management of the survey were carried out by the research team. Developing the questionnaire involved four steps:

1) Brainstorming relevant questions that uncover the aims of the study

2) Refining and organizing the questions into a structured questionnaire for data collection

3) Designing and implementing a pilot online survey

4) Modifying the survey approach and questionnaire as a result of lessons learnt

These steps are described below and followed by details regarding the sample generated in the final survey.

Initial question brainstorming

The research team started by identifying three main themes:

- Demographics
- Experience in designing for AM
- Knowledge of Design for AM

These themes represented the data the survey aimed to capture in broad terms. Subsequently, for each of the themes, the team brainstormed a series of questions that could uncover the experience and knowledge of the participants on the topic of DfAM. The questions covered basic data regarding the participants as well as specific information regarding their professional experience in DfAM and their overall familiarity with AM. For each of the three themes the research team initially identified ten questions that intended to uncover the relevant data.

Initial structured questionnaire

Those questions were further reviewed, integrated and systematised resulting in a more structured draft made of five sections:

- Demographics
- Experience in DfAM
- Using AM as a production process
- Knowledge of AM
- Views of AM as a production process

Open-ended and closed questions were determined along with sets answers for the closed questions. A routing system was also drafted in order to open specific questions only to participants with relevant experience in designing end-user components for series production in AM.

Initial on-line pilot

The draft questionnaire was then implemented using the on-line survey platform BOS (www.onlinesurveys.ac.uk) and then piloted in one of the research institutions among staff members with experience in DfAM. The online survey platform allowed easy distribution of the survey among the design community and the automation of the routing structure. This on-line survey resulted in eleven sections.

1) **Introduction**
2) **About you** – containing demographic information about the participant
3) **Experience in DfAM** – evaluating the experience in using AM in design practice
4) **Using AM for Series Production of End Use Products or Components** – explicitly included for routing the participants with relevant experience on DfAM to more specific questions
5) **Using AM for Series Production of End Use Products or Components** – Investigating relevant experience in designing for AM with specific focus on a specific component or product the participants have designed for AM
6) **Design Aids for AM** – aimed at surveying which tools designers have used to support DfAM activity
7) **Reasons for not using AM for Series Production** – exploring why participants have never designed end-user components for AM
8) **Design for AM Knowledge** – exploring the perceived level of knowledge
9) **Design for AM Knowledge** – Enquiring about their interest in DfAM knowledge
10) **Preferred formats for DfAM Knowledge** – examining which formats designers would prefer to use to access DfAM knowledge
11) **Interview** – section added to recruit potential participants for a follow-up in-depth interview

Redesigned survey instrument and approach

The pilot of the on-line survey verified that the target audience was interpreting the questions as intended and that the responses contained a rich set of relevant data points. The initial feedback indicated the need for minor modifications. Detailed descriptions of AM processes and information formats with links to examples were added to reduce misinterpretations. After these modifications, the survey was made available for distribution.

Final survey

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 final survey comprised of eleven sections:

Section 1 – Background of the project, aims of the survey and a reminder about the Data Protection Act

Section 2 – Demographic information regarding country of employment, profession, job title, type of employment and sector

Section 3 – Identifying the level of participant expertise in using AM for modelling and prototyping, producing tooling, jigs or fixtures and for the series production of end-user products or components

Section 4 – directed participants with relevant experience in designing end-user components for AM to a more in-depth set of questions

Section 5 – for participants with relevant experience in DfAM, gathering information about one specific end-user product or component designed by the participant and made in series using AM. This section explored some general and specific information about the component/product (component or product, overall dimensions, production volume, material, AM process used in production, specific machine, main reasons for selecting AM, main limitations of using AM as production process, other processes considered)

Section 6 – explored the design aids used to design the component. This considered some general information about the design process involved, design rules, guidelines, principles used in the design process, how this information was retrieved and at which stage of the design process it was used

Section 7 – for participants who did not indicate experience in designing for AM, this section captured the reasons why they had never designed for AM

Section 8 – sought to elicit the perceived level of knowledge in DfAM of the participants and asked which sources of information they considered useful for acquiring new knowledge in DfAM. Then it asked at which stage of the design process this knowledge should be used. In addition, the usage of design tools generally related to AM such as topology optimisation and generative design was explored

Section 9 – sought to elicit the perceived need of designers for more information regarding DfAM

Section 10 – further investigated this need by seeking to elicit what information or knowledge designers would benefit from, and in which format this knowledge should be conveyed

Section 11 – finally, section 11 invited participants to leave their email address if they were willing to take part in a follow-up qualitative interview.

Figure 1 presents the questionnaire structure with the sections and the relative questions included while Table 1 shows the list of questions.

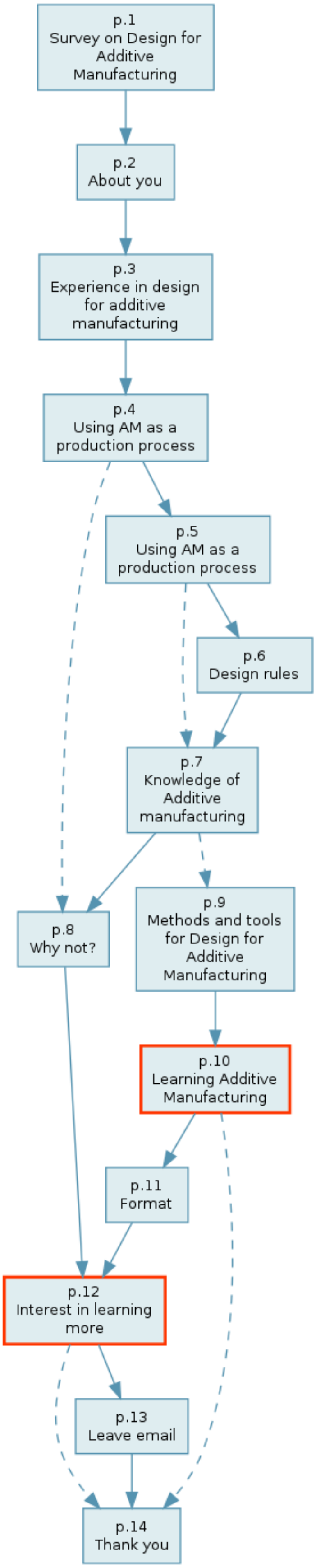

Figure 1: Flow chart for the survey questions

Table 1: Survey Details

Section	Question or text	Format of data output
S1: Introduction	AM also known as 3D Printing is a family of production technologies, which unlike conventional processes; make components by adding material layer by layer. These processes are well known in prototyping; however, they are also becoming competitive alternatives to conventional manufacturing processes for series production, providing new opportunities for design practice. This survey aims to understand what designers know and do when designing end user products or components for series production made in AM and how they can be supported when they are facing the design of products or components that will be produced in series with AM. All data provided will be strictly confidential and handled in accordance with the Data Protection Act. Neither you nor your company will be named in any public reports produced from this work without your written permission.	
S2: About you	Q1: Which country do you work in?	Choice: one country out of the list of countries retrieved from https://www.state.gov/misc/list/
	Q2: How do you define yourself? Options: Design maker / Craftsman; Industrial designer; Product designer; Design engineer; Architect; Manufacturing Engineer; Other	Choice: one or more out of six. "Other" option accompanied by free form text field
	Q3: What is your Job Title?	Free form text
	Q4: How many years of experience as a designer do you have?	Choice: one out of five years of experience groups
	Q5: Describe your employment. Options: Freelance or self-employed; In-house manufacturer; Design consultancy	Choice: one or more out of six
	Q6: What is the principal sector which you design for?	Free form text
S3: Experience in designing for AM	Q7: As a designer, how often have you designed components for AM over the last 5 years? Options: For modelling and prototyping; For producing tooling, jigs or fixtures; For the series production of end-use products or components	Each item scored on a 1-5 scale, where 1 = Never, 5 = Routinely (More than 4 times per year)
S4: Experience in designing end-use components for AM	Q8: Have you ever designed any end-use product or component for which AM was a production process for series (i.e. not prototyping, not tooling and not just a one off)?	Yes/No response. Yes directs to section S5, No to section S6
S5: End-use component designed for additive	With one specific end-use product or component you designed in mind, that was made in series production with AM, could you please tell us:	
	Q9: What was the product or component?	Free form text
	Q10: If it was a component, what was the product into which the component fit?	Free form text
	Q11: What were the dimensions of this product or component?	Free form text
	Q12: What was the total volume for the series production of this product or component? Options: 1-10, 11-100, 101-1000, 1001-10000, Over 10000	Choice: one out of five production volume groups
	Q13: What was the material? Options: Plastic, Metal, Ceramic	Choice: one out of three material categories
	Q14: Can you be more specific?	Free form text
	Q15: Do you know what specific AM process was used for series production? Since there are many different names for AM, if you need more information in order to answer this question, please click the button More info below or visit the website: The 7 categories of AM [link to categories description]. Options: VAT; photopolymerization; Material Jetting; Binder Jetting; Material Extrusion; Powder Bed Fusion; Sheet Lamination; Direct Energy Deposition; Other	Choice: one out of seven. "Other" option accompanied by free form text field
	Q16: Do you remember the specific machine used for production?	Free form text

	Q17: Can you describe the three main reasons why that specific process was selected for series production?	Free form text
	Q18: What were the main limitations of using AM as a series production process?	Free form text
	Q19: Did you consider any other production technology during the design process	Free form text
	Q20: Did you follow any specific design rules or design guidelines to help you design this product or component?	Yes/No response. Yes directs to section S6, No to section S7
S6: DfAM used in designing components	Q21: Which design rules or guidelines did you follow?	Free form text
	Q22: Considering this product or component, how did you find these design rules or guidelines? Options: Reading books; Looking at how products are made; Experimenting with AM technologies; Speaking with experts; Attending a training course/s; Visiting trade fairs; Reading trade magazines; Surfing on the Internet; Previous experience in AM; Other	Choice: one or more out of nine. "Other" option accompanied by free form text field
	Q23: In which stage of the design process did you apply these rules or guidelines? (tick more than one if needed). Options: Brief setting; Conceptual design; Embodiment design; Detail design	Choice: one or more out of four.
S7: Reasons for not using AM for production	Q24: Could you briefly describe the reasons why you have never used AM for series production?	Free form text
S8: Knowledge of DfAM	Q25: How do you rate your knowledge of Design for AM?	Each item scored on a 1-5 scale, where 1 = Very poor, 5 = Very good
	Q26: For each of the following sources of information, please rate them for usefulness in informing your personal knowledge of Design for AM. Options: Expert tuition; Training courses; White papers produced by suppliers; Manuals; Books; Wiki; Blogs; Journal papers; Magazine articles; Personal experience; Other products or components made with AM; Trade fairs; Software based support tools; Bespoke company tools or methods; Other	Each item scored on a 1-5 scale, where 1 = Never used, 5 = Extremely useful
	Q27: In your opinion, in which stage of the design process should Design for AM knowledge be considered? (tick more than one if needed). Options: Brief setting; Conceptual design; Embodiment design; Detail design	Choice: one or more out of four.
	Q28: When you design products or components for AM, do you use any of the following software tools? Options: Topology optimization; Generative design	Each item scored on a 1-5 scale, where 1 = Never, 5 = Almost always
S9: Benefit for additional information on DfAM	Q29: As a designer, would you benefit from more information regarding Design for AM?	Yes/No response. Yes directs to section S10, No to section S12
S10: Preferred format for DfAM knowledge	Q30: Which kind of information about Design for AM would you like to know more of?	Free form text
	Q31: In which formats would you prefer to access this information? If you are not familiar or doubtful with some of the answers below, please click More Info below and you will find a definition and some examples for each of the answers. [Description of the categories with links to examples]. Options: Textbook; Manual; Handbook; Catalogue of case studies; Images bank; Library of products or components made with AM; Exhibition of products or components made with AM; Online videos; Blog; Wiki; Website; Short training course; Long training course; Talking with AM experts; Sample piece/s made with AM; Smartphone app; CAD Software; Decision support tool; First person hands-on experience; Virtual or augmented reality; Makerspace; Forum; Other	Each item scored on a 1-5 scale, where 1 = Not at all, 5 = Extremely
S11: Follow-up interview	Q32: Would you be willing to take part in a follow up interview?	Yes/No response. "Yes" option accompanied by free form text field
S12: Closing message	Thank you very much for helping us in this research. Feel free to pass this survey to your friends and colleagues or to invite anyone you think could be interested.	Free form text field

If you would like to remain informed about our project on Design for AM, you can visit our website at [link to the project website] or leave your email below.

Final Survey Sample

A non-probabilistic accidental sampling strategy was adopted since the study aimed at uncovering potential hypotheses surrounding the topic of DfAM and because of the difficulty of obtaining an statistically relevant list of international professional designers. This sampling strategy had the advantage of allowing the relatively easy collection of a large number of responses in a short period.

The survey was actively distributed online by

- Email to design practitioners retrieved through the websites 'The directory of design consultants' and 'Coroflot' (www.designdirectory.co.uk, and www.coroflot.com)
- Notices placed on the Linked In groups: Industrial Design, Product Design, 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 Additive Manufacturing & 3D Printing and Develop 3D
- Via the newsletters of the 3D Printing Industry and the British Industrial Design Association (BIDA)
- Private messages to Linked In members with relevant backgrounds in product and industrial design

The survey went live 1st June 2016 and the research team actively sought participants until 30th June when the target of 100 responses was achieved. The online survey was left open, without any further attempt to recruit more participants, for one month further and continued to collect responses, until it formally ended on 31st August 2016.

Analysis

Closed questions

Data from the closed questions were analysed by employing descriptive statistics and non-parametric test from the statistical software SPSS (v23).

Likert scale data were analysed using an index obtained by multiplying the value of the answer (e.g. 1='Never', 2='Seldom' 3='Sometimes' 4='Very often' 5='Always') by the frequency of respondents. This index allowed us to create a ranking of the answers.

Open-ended questions

Open-ended questions were analysed with a Content Analysis approach performed using NVivo 10 for Windows. To explore the diversity and richness of material gathered an inductive approach was applied to open-ended questions, enabling the categories to emerge from the responses. Half of the answers were simply enumerations of keywords, (e.g. accuracy, cost, material performance) without additional explanation and these keywords formed the basis for categories.

Categorisation was performed by examining each response at least twice. Firstly, keywords in the text clearly addressing a 'need to retrieve' (Question 1) or a 'need to capture' (Question 2) were identified. Secondly, the texts were examined at the sentence level to assess whether additional needs were discernible from larger fragments, without double counting articulated needs. Throughout this process, categories were identified and named in terms of the natural language of the text, rather than more abstract terms from design theory to remain as close as possible to the original wording and the respondents' intentions.

Results

Population of the survey

A total number of 730[1] visitors accessed the survey with 110 completing the entire questionnaire. The overall drop-out rate was 15.1%.

All the 110 responses collected were considered complete and included in the analysis.

Respondents from 25 countries participated in the study; the overall majority (70%) were from the United Kingdom, Europe and North America. In more detail 29.1% (n=32) were from the United Kingdom, 16.4% (n=18) from the United States, 12.7% (n=14) from Italy, 10.0% (n=11) from Germany and 7.3% (n=8) from Canada. India and China accounted respectively for 2.7% (n=3) of the population. While Australia, Ireland, Sweden and Switzerland for 1.8% (n=2) separately. The remaining 11.8% (n=13) was made by a large pool of countries comprising Turkey, Taiwan, Spain, Singapore, Serbia, New Zealand, Malaysia, South Korea, Indonesia, Finland, Austria and Andorra.

Product Designers accounted for 40.0% (n=44), Industrial Designers accounted for 39.1% (n=43) and Design Engineers for 30.9% (n=33) of the total. 10.0% (n=11) were Manufacturing Engineers and 7.3% (n=8) were Maker/Craftsman. 15.5% specified 'Other' such as Educator, Hobbyist, Program Manager, Software Product Strategist, Student, Technician, Interior Designer, Researcher, UX Designer and Engineer. This diversity gives a first indication about the variety of professions potentially attracted by AM. The role sum exceeds 100% because some respondents indicated that they had more than one definition and we double counted such responses.

Regarding the job title, the open-ended answers were simply keywords, such as manager, industrial designer or student. These keywords formed an obvious basis for clustering, resulting in the following categories: Industrial Designer (n=14, 12.7%), Designer (n=9, 8.2%), Product Designer (n=5, 4.5%), UX designer (n=3, 2.7%), Industrial Designer/Design Engineer (n=2, 1.8%) and Interior Designer (n=1, 0.9%) accounted for roughly a third (30.9%, n=34) of the population. Director (n=17, 15.5%), Manager (n=8, 7.3%), General Manager (n=5, 4.5%) and Partner (n=1, 0.9%) accounted for roughly another third (n=31, 28.2%). Design Engineer (n=14, 12.7%), Mechanical Engineer (n=6, 5.5%), Engineer (n=5, 4.5%), Manufacturing Engineer (2.7%), Systems Engineer (n=1, 0.9%), Optical Engineer (n=1, 0.9%) accounted for a quarter (n=27, 24.5%). Researcher counted for 2.7% (n=2), while Student and Technician for one (n=1, 0.9%) respectively. The 9.1% (n=10) of the population did not provide any job title.

The relative majority (38.2% n=42) of the respondents had between 1 and 5 years of professional experience. 20.0% (n=22) had between 6 and 10 years, 15.5% (n=17) between 11 and 15 years, 10.0% (n=11) between 16 and 20 years, and 16.4% (n=18) had more than 20 years.

Almost half (47.5% n=57) of our sample were employed in design consultancies, roughly a third (30.8% n=37) in-house for manufacturers and 21.7% (n=26) were freelancers or self-employed. The employment sum exceeds n=110 because some indicated that they had more than

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[1] This number indicates the number of times the survey was accessed. If one person 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.

one type of employment and we double counted such responses.

In response to the open-ended question regarding industrial sector, 124 sectors were identified. Of those 26.6% (n=33) were consumer goods, 17.7% (n=22) medical devices, 8.9% (n=11) industrial machinery, 7.3% (n=9) consumer electronics, 5.6% (n=7) automotive, 4.0% (n=5) scientific instruments, 4.0% (n=5) telecom and software and 15.3% (n=19) other industries, furniture, architecture, education, energy, sport goods, aerospace, footwear, marine, museums, packaging and retail. 6.5% (n=8) did not disclose their industry affiliation and 4.0% (n=5) provided a generic definition such as ‘all’ or ‘none’.

Table 2 shows the respondent progress in the different sections of the survey. Section 1 and 2 presented the maximum number of visitors leaving the survey with respectively 459 and 100 drop-outs. The comparatively high dropout rate at the introduction (section 1) may indicate the non-familiarity of the participants with the topic of the survey or the terminology adopted. Although reported in brackets in the Introduction section, the widespread terminology 3D Printing was not used in the survey in preference to the term Additive Manufacturing. One explanation could be that the term Additive Manufacturing was not widely known and it increased the dropout rate at Section 1.

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Table 2: Respondent progress and drop out

Section	Respondents dropout (n)
1	459
2	100
3	11
4	3
5	25

6	8
7	10
8	0
9	7
10	7

Table 3: Participants' demographics

Characteristic	**Frequency**
Country	
United Kingdom	32
United States	18
Italy	14
Germany	11
Canada	8
China	3
India	3
Others	21
N/A	1
Profession (n=156 answers/n=110 respondents)	
Product Designer	44
Industrial Designer	43
Design Engineer	33
Manufacturing Engineer	11
Maker / Craftsman	8
Other	17
Job title	
Designer	34
Manager/Director	31
Engineer	30
Other	5
N/A	10
Experience in Design (years)	
1-5	42
6-10	22
11-15	17
16-20	11
Over20	18
Type of Employment (n=120 answers/n=110 respondents)	
Design consultancy	57
In-house manufacturer	37
Freelance or self-employed	26
Principal sector (n=124 answers/n=110 respondents)	
Consumer Durables & Apparel	48
Health Care Equipment & Services	22
Capital Goods	16
Technology Hardware & Equipment	10
Automobiles & Components	7
Consumer Services	3
Energy	2
Transportation	1
'Generic'	5
N/A	8

The practice of Additive Manufacturing in Design

For modelling and prototyping, results show how the overall majority (n=77, 70.0%) of our sample have designed either routinely (n=64, 58.2%) or very often (n=13, 11.8%) components prototyped using AM over the last five years. 11.8% (n=13) had used AM for prototyping 3 to 5 times and 8.2% (n=9) rarely over the same period. Only 10.0% (n=11) had never designed components for modelling and prototyping using AM.

Regarding the design of tooling, jigs or fixtures made using AM, our sample divided into three roughly equal groups. One third (n=37, 33.8%) had never designed tooling, jigs or fixtures made in AM in the past five years. Another third (n=38, 34.6%) indicated either rarely (n=21 19.1%) or sometimes (n=17, 15.5%). The remaining 31.8% (n=35) expressed a more consistent design practice in this area indicating 14.5% (n=16) very often and 17.3% (n=19) routinely.

Remarkably, the overall majority (n=66, 60%) indicated that they had never designed end-user components made in series production with AM. Another 19.1% (n=21) selected either rarely (n=15, 13.6%) or sometimes (n=6, 5.5%). While only 20.9% had designed end-user components or products for AM either very often (n=10, 9.1%) or routinely (n=13, 11.8%).

An additional question (Q8) in the following section asked explicitly if participants had ever designed an end-user product or component made using AM. The result of this question, 25.5% (n=28) yes and 74.5% (n=82) no, further corroborated the previous results showing how only a minority had experienced designing for AM.

These results lead us to conclude that while designing for prototyping and modelling in AM seems to be an established practice among our population (only n=11, 10.0% answered never), designing for tooling, jigs or fixtures and designing for series production of end-user components presented a completely different scenario. In designing for producing tooling, jigs or fixtures one third (n=37 33.6%) indicated never but the remaining overall majority (n=73 66.4%) had experienced it at least once, showing how AM production of tooling, jigs and fixtures is probably not routinely utilised, but it is recognised and expanding. These results seem to reveal that AM is not generally utilised as a production process by our sample. In fact, only a relatively limited number of participants (n=28, 25.5%) seem to have designed end-user components for AM at least once.

Table 4: Experience of DfAM of participants

Characteristic	Never	Rarely (1 to 2 times in 5 years)	Sometimes (3 to 5 times in 5 years)	Very Often (1 to 3 per year)	Routinely (More than 4 per year)
For modelling and prototyping	11	9	13	13	64
For producing tooling, jigs or fixtures	37	21	17	16	19
For the series production of end-user components	66	15	6	10	13

Experience in Designing for AM

Section 5 presents the experiences of the participants who have designed end-user components for AM. Participants who answered ‘yes’ in the previous section 4 and therefore indicated that they possess experience in designing end-user components made in series production using AM were routed into this section. Although 28 participants positively answered section 4, 4 respondents were excluded from the analysis because their answers were incomplete. The remaining 24, (21.8% of the total survey population), constituted the basis for this analysis.

Components design for series production in AM

In questions 9 and 10, participants were asked to provide the name of a component they designed for AM along with the name of the product that the component was part of. As shown in Table 5, 24 components, one for each participant, were indicated by the respondents with 19 related products. These components were further classified by industrial sector in 8 categories Aerospace, Automotive, Consumer electronics, Consumer goods, Industrial goods, Medical devices, Safety equipment and Scientific Instruments. A category called Generic was added to cluster the components that could not be clearly classified under any specific industrial sector e.g. Component, Mounting bracket and Mounting fixture. The two most represented categories were Consumer goods (n=6) and Medical devices (n=5) followed by Consumer electronics (n=3), Industrial goods (n=2) and Scientific Instruments (n=2). The industrial sectors Aerospace, Automotive and Safety equipment were represented only by one case each.

Table 5: Summary of components produced in series with AM with relative products and Industrial sector

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[b] 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[c] 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

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[b] Since this material-technology combination is not possible, we gave priority to the ‘Material’ answer because it came from an open-ended question. In this case, we considered the process as Material Extrusion.

[c] Since this material-technology combination is not possible, we considered this entry as Powder Bed Fusion.

‘Labware’	‘Robot stage’	‘Scientific instruments’	127, 85, 60	101-1000	Nylon	Material Extrusion

Regarding the size of the components designed for AM, Table 6 reports the aggregated measures respectively for the bounding dimensions in the X, Y and Z-axes. These measures comprise the arithmetic mean, the minimum and maximum value, the median, the mode and the standard deviation. In each of these measures, the dimension in the Z-axis resulted the lowest with a mean roughly half of the other two dimensions.

The T-test presented in

Table 7 statistically corroborated the significant difference between the dimensions in the Z axis (M=61.2, StDev=66.3) and those on the X (M=138.7, StDev=103.8), t(24)=4.06, p≤.01, $CI_{.95}$ 40.49, 123.09 and Y axis (M=111.8, StDev=122.9), t(24)=-2.86, p≤.01, $CI_{.95}$ -100.34, -16.52

Table 6: Aggregate size of the components

Axis	Frequency	Mean	Min	Max	Median	Mode	StDev
X(mm)	24	138.7	10	400	123	200	103.8
Y (mm)	24	111.8	10	500	60	50	122.9
Z (mm)	24	61.2	7	280	48	15	66.3

Table 7 T-test results for size comparison in X, Y and Z

	t	df	p	95% Confidence Interval
X: - mm - Z: - mm	4.06	24	0.000*	40.488 - 123.083
Z: - mm - Y: - mm	-2.86	24	0.008*	-100.336 - -16.522
Y: - mm - X: - mm	-1.68	24	0.105	-51.935 - 5.221

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* p≤0.01

The total production volume of these components was between 11 and 1000 pieces for more than two-thirds of the participants (n=17,) with roughly one third between 11 and 100 (n=8) and another third between 101 and 1000 (n=9). 20.8% (n=5) had a total production volume of less than 10 pieces while the remaining 8.3% (n=2) had a total production volume between 1001 and 10000. None of the cases reported a total production volume of more than 10001 pieces.

Plastic was used by almost all respondents in our sample (n=22, 91.7%) with only two participants reporting metal (8.3%, n=2). Polyamide (29.2%; n=7) and ABS (20.8%; n=5) were the most used polymers. Other polymers were Polyurethane (4.2%; n=1), Polycarbonate (4.2%; n=1), Epoxy resin (4.2%; n=1) and PLA (4.2%; n=1) while for the metals only one participant specified stainless steel. A quarter (n=62, 5.0%) did not specify any material.

Six of the seven categories of AM technologies were mentioned. Only sheet lamination was not indicated. Material Extrusion and Powder Bed Fusion were the most frequently reported (n=7) each accounting for the 29.2%. VAT photopolymerization was indicated by a quarter of the participants (n=6, 25.0%). Material Jetting (8.3% n=2), Direct Energy Deposition (4.2% n=1) and Binder Jetting (4.2% n=1) together accounted for the remaining 16.7%.

Over half of those surveyed (n=16, 66.7%) mentioned the commercial name of the machine used. Inside this group, a large majority (n=15, 62.5%) specified the name of a professional 3D printing machine with only one indicating a so-called desktop machine. *Fortus 250* and *3D Systems sPro 60* were indicated twice.

Table 8: Machines used to produce the components

Type of machine	Answers	Frequency
Professional machine	‘Fortus 250’, ‘EnvisionTec Perfactory’, ‘Stratysys Dimension’, ‘3D Systems sPro 60‘, ‘fortus’, ‘Various, but usually EOS P760’, ‘SLA-5000’, ‘Fortus 250’, ‘Renishaw 250’, ‘HP uPrint,’ ‘Projet 660’, ‘objet eden’, ‘3D Systems - sPro 60’, ‘EOS something’ and ‘Drumlord Ltd...’	15
Desktop machine	‘3 Makerbot Replicator 2X machines’	1
Generic	‘3d printing machine’	1
N/A	No’, ‘No’, ‘no’, ‘no’, and ‘no’	7

Reasons for using AM as a production process

Regarding the reasons for using AM for series production, we observed that while the majority (n=20, 83.3%) of the participants provided reasons for using AM instead of conventional manufacturing, 4 (16.7%) participants provided the reasons for choosing a specific AM technology. Considering this, we analysed the reasons provided by these two groups separately.

Table 9 provides a summary of the reasons for using AM compared with conventional manufacturing. The main reasons mentioned by our participants were Low Volumes (n=6, 25.0%), Complex shape (n=5, 20.8%), Speed (n=5, 20.8%), Cost (n=5, 20.8%), Shape manufacturability (n=4, 16.7%) and Customization (n=3, 12.5%). Many other reasons were mentioned only once or twice. These reasons included *Part consolidation*, *Easiness*, *Constant feedback*, *Accessibility* and *Short development time* indicated by two participants (n=2, 8.3%). *Lightweight*, *Internal Structure*, *Finishing*, *No stock*, *Before moving to CM*, *No need for aesthetic qualities*, *Confidentiality*, *Precision*, *Organic shape*, *No need for tooling*, *Nano coating*, *Low post processing*, *Cryogenic performance*, *Optical properties* and *Suitability for implants* indicated once each (n=1, 4.2%).

Seven reasons emerged for choosing a specific AM technology. These reasons were *High resolution* (n=2, 8.3%), *Reliability* (n=2, 8.3%), *Material properties including the possibility of using thermoplastic materials with known material properties* (n=2, 8.3%), *Access to the AM technology* (n=1, 4.2%), *Lack of support structures* (n=1, 4.2%), *Low cost* (n=1, 4.2%) and *Better finishing* (n=1, 4.2%).

Table 9: Reasons for using AM as a production process (n=54 reasons/n=24 respondents)

Category	Answers	Frequency
‘Low Volumes’	‘Short Run’, ‘We use this production technique for limited runs’, ‘cheaper for small series production’, ‘Quantity needed (low)’, ‘Small quantity’ and ‘small number of parts’	6
‘Complex shape’	‘Designs to (too) complex to manufacture otherwise’, ‘Complex shape required’, ‘Geometric freedom to fabricate complex shapes’, ‘unique geometry’ and ‘complex form’	5
‘Speed’	‘Speed’, ‘quick’, ‘Quick turnaround on iterations’, ‘Quicker and cheaper than tooling for moulding at this volume’ and ‘fast build times’	5
‘Cost’	‘Cheap costs’, ‘Cost’, ‘Volume of production was cheaper than quoted tooling services’ and ‘Quicker and cheaper than tooling for moulding at this volume’	5
‘Shape manufacturability’	‘Impossible to cast’, ‘Designs to (too) complex to manufacture otherwise’, ‘There was a negative draft angle inside’ and ‘Geometric freedom to fabricate complex shapes’	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

Main limitations for using AM as a production process

The most cited limitation of AM as a production process indicated by our sample was cost (37.5% n=9) including the specific limitations *Cost of Materials* (n=1, 4.2%) and *Cost due to build time* (n=1, 4.2%). Other significant limitations were *Post processing* (16.7% n=4), *Labour for post finishing* (n=1) and *Long post processing required* (n=1); *Productivity* (16.7% n=4) including *Production time* (n=3) and *Materials* (16.7% n=4) including the subcategories *Mechanical properties* (n=2), *Limited materials available* (n=1) and *Waste of material* (n=1). Additional limitations (37.5%) were *Accuracy* (n=2), *Surface finishing* (n=2), *Quantities* (n=1), *Repeatability* (n=1), *Limited ability to create hole features that incorporate threads* (n=1) and *Flexibility* (n=1). Curiously one participant also mentioned (there are) *No limitations if the product is optimized for additive*.

Table 10: Main limitations for using additive manufacturing as a production process (n=48 limitations/n=24 respondents)

Category	Subcategory	Answers	Frequency
'Cost'		‘Cost’ , ‘High cost ‘, ‘cost’, ‘High cost.’, ‘Expensive’, ‘cost’ 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 labor’	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
	'Build platform size'	‘Build platform size at maximum resolution.’	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

When asked if other production technologies rather than AM were considered during the design process, the overall majority (70.8% n=17) responded positively. 10 participants also reported which technologies were considered. An overview of these technologies is provided in Table 12. 20.8% (n=5) reported that no other technologies were considered during the design process. Two participants did not answer this question.

Table 11: How many participants considered alternative processes

Categories	Frequency
‘YES’	17
‘NO’	5
N/A	2

Table 12: Which alternative processes were considered

Categories	Frequency
‘FDM’	2
‘SLS’	2
‘Injection Moulding’	2
‘Machining’	1
‘Liquid Silicone Rubber Injection Moulding’	1
‘Wax RP’	1
‘EBM’	1
‘Tooling’	1

Design aids

The majority of our sample (n=17) reported that they followed specific design rules or guidelines for AM whilst designing components for series production, whilst 6 respondents did not answer this question.

Table 13 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). 5 respondents stated that they had 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 *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.

Table 13: Design aids followed by the participants (n=25 design aids/n=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

Regarding the sources used to gather knowledge on DfAM, over half indicated the sources *Previous experience in AM* (62.5% n=15), *Experimenting with AM technologies* (58.3% n=14) and *Speaking with experts* (54.2% n=13). 45.8% (n=11) specified *Looking at how products are made* while one third (33.3% n=8) indicated respectively *Reading books* and *Surfing on the Internet*. *Attending a training course/s* (20.8% n=5), *Visiting trade fairs* (16.7% n=4) and Reading trade magazines (8.3% n=2) were indicated only by a low number of respondents. One respondent also chose *Other* and specified *3D modelling analysis*.

Table 14: Sources for DfAM knowledge

Category	**Frequency**
'Previous experience in Additive manufacturing'	15
'Experimenting with AM technologies'	14
'Speaking with experts'	13
'Looking at how products are made'	11
'Reading books'	8
'Surfing on the Internet'	8
'Attending a training course/s'	5
'Visiting trade fairs'	4
'Reading trade magazines'	2
'Other'	1

When asked at which stage of the design process they adopted DfAM knowledge, 25.0% (n=6) indicated at all stages of the design process, while 20.8% (n=5) only at the detail design stage. Another 8.3% (n=2) indicated respectively at embodiment and detail design, at conceptual design, at embodiment design and at detail design. Brief setting and detail design (4.2% n=1), embodiment design (4.2% n=1) and conceptual design and detail design (4.2% n=1) were only selected once. Six participants (25.0% n=6) did not answer to this question. Interestingly, the Detail design stage was mentioned by all the participants except one.

Table 15: 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

Reasons for not using AM to produce end-user components

The 82 participants who reported to have never designed for AM were directed to Question 28, which enquired about their reasons for having never designed end-use components for series production in AM. This question uncovered 29 factors for not using AM for series production (Table 16). More than a third of these participants (n=31) indicated cost as their primary concern. 8 respondents indicated that AM *has never been required* in their professional career. Other key reasons related to perceived limitations in the physical characteristics of 3D 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.

Table 16: Reasons for not using AM for end-user components (n= 132 Reasons/n=82 respondents)

Category	Example comments from respondents	No.
'Cost'	'Cost too high', 'economic requirements' and 'Metal parts can be expensive'	32
'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
'Has never been required'	'Has never been required', 'It has never been requested to me', 'Never thought' and 'Didn't happen'	9
'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
'Speed'	'Not fast enough', 'too long to produce an object' and 'Slow process'	8
'Surface finishing'	'poor surface finish', 'Surface finish' and 'Typically gives a poor surface finish'	7
'Production Volume'	'We often design relative high volume products (1,000'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
'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
'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
'Accuracy'	'The process often does not support either structural, size/location tolerance', 'Dimensional inconsistency', 'inaccurate (tolerancing)'and 'The accuracy of making products'	5
'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
'Reliability'	'seems not reliable', 'Dimensional inconsistency', and 'Process proved not to be as controlled as machining'	4
'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
'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
'Aesthetics'	'Aesthetic' and 'Quality and appearance concerns generally, despite the short term and long term cost advantages.'	2
'Durability'	'Perceived lack of durability of the component' and 'Durability'	2
'Limited available materials'	'limited materials selection' and 'limitation in material choice'	2
'Complexity of the AM process'	'Complexity' and 'It seems like the current technologies is still sufficient and AM process need to be simpler.'	2
'Chemical and environmental stability'	'Poor chemical and environmental stability of available thermoplastics and resins'	1
'Not ready for series production'	'seems not reliable and ready for series production'	1
'Post processing'	'finishing is required'	1
'Resources efficiency'	'Currently, it is not a cost or resource-effective manufacturing process.'	1
'Limitations for customized production'	'There is too much limitation for customize production as well.'	1
'Standards'	'Not recognize by standard organization (CSA, UL, CE, etc.)'	1
'Size'	'Mainly because of the cost or limitations in size'	1
'Technical support'	'The limitations of technical support'	1
'Supplier availability'	'supplier availability (most being interested in higher value prototype work)'	1
'Requirements'	'When considering production quantities and requirements there are far better solutions',	1

'Perception'	‘Still viewed as a prototyping process’	1

Knowledge of design for AM

The participants indicate confidence about their self-perceived knowledge of DfAM. Most of the responses (80.0%) rated their level of knowledge between the levels Fair (25.7%), Good (32. 1%) and Very good (22.9%). Only 19.3% (n=21) indicated possessing Poor (n=15 13.8%) or Very poor knowledge (n=6 5.5%).

Table 17: the perceived level of knowledge in DfAM

Category	Extremely useful	Very useful	Somewhat useful	Not useful	Never used		
	n	n	n	n	n	Mdn	IQR
'Knowledge of DfAM'	6	15	28	35	25	1	4

Table 18: the perceived level of knowledge in DfAM

Category	Perceived Level of Knowledge
'Knowledge of DfAM' (n=109)	3.5

Approches for gathering DfAM Knowledge

Our analysis shows that personal experience was considered the most useful approach to gather DfAM knowledge (Mdn=5, IQR=1). Many respondents indicated referring to other products or components made with AM (Mdn=4, IQR=1). Expert tuition (48.2%) and training courses (40.7%) were also found useful by many respondents. However, a roughly equal number (training courses N=36 and expert tuition n=37) reported to have never used these approaches (Mdn=3, IQR=3). Journal papers and bespoke company tools or methods showed a similar pattern but with lower support in terms of usefulness (~n=10 less in extremely and very useful). Blogs, manuals, software based support tools, white papers produced by suppliers and wikis received the same results in terms of usefulness but they have been used at least once by the majority of the sample (Mdn=3, IQR=2). Equally, books, magazine articles and trade fairs presented similar results. However, there was slightly more consensus around them being only somewhat useful (Mdn=3, IQR=1).

Sixteen participants (17.3%) specified also other approaches. Speaking with experts and peers was mentioned by eight participants (7.3% n=8). University courses and experience were also indicated by more than one participant (1.8% n=2). The remaining were experimentation, assistive software tool, search engine, competitor product analysis, samples and online forums.

Table 19: Usefulness of different approaches for gathering DfAM knowledge

Category	Never used	Not useful	Somewhat useful	Very useful	Extremely useful				
	n	n	n	n	n	N/A	Mdn	IQR	Usefulness
Personal experience	5	2	9	29	64	1	5	1	4.3
Other products or components made with additive manufacturing	10	6	34	41	18	1	4	1	3.5
Blogs	22	9	40	26	12	1	3	2	3.0
Expert tuition	37	4	15	36	17	1	3	3	2.9
Manuals	18	9	53	25	4	1	3	2	2.9
White papers produced by suppliers	21	9	49	22	8	1	3	2	2.9
Software based support tools	22	13	41	24	9	1	3	2	2.9
Training courses	36	3	25	34	11	1	3	3	2.8
Wiki	23	19	38	21	8	1	3	2	2.7
Books	25	17	40	21	6	1	3	1	2.7
Trade fairs	23	16	44	26	0	1	3	1	2.7
Magazine articles	24	15	50	15	5	1	3	1	2.7
Bespoke company tools or methods	37	9	30	25	8	1	3	3	2.6
Journal papers	34	11	33	26	5	1	3	3	2.6
Other	75	7	16	4	5	3	1	1	1.7

Table 20: Other useful approaches specified by the participants

Category	Answers	Frequency
‘Speaking with experts and peers’	‘speaking with Stratasys engineers’, ‘Talking to machine operators’, ‘Knowledge from the employees & technicians of 3D printing houses’, ‘Discussions with peers and colleagues from other industries’, ‘Asking colleagues’, ‘former classmates’, ‘colleagues experience’ and ‘Similar partners’	8
‘University course’	‘University course in plastic engineering’ and ‘University’	2
‘In-house experience’	‘In house experience’	1
‘First-hand experience’	‘first-hand experience’	1
‘Experimentation’	‘Experimentation’	1
‘Assistive software tool’	‘lightweight designing software’s like topology optimization software’s, also automatically identifying overhangs, length to which machine not required support for particular angle, curve editing & surface editing & dimensioning of these make as much as easy user interface for freeform fabrication’	1
‘Search engine’	‘Google search’	1
‘Competitor Product Analysis’	‘competitor product analysis’	1
‘Samples’	‘Samples’	1
‘Online forums’	‘On-line Forums – printer specific’	1

The most suitable stage of the design process for DfAM

21.8% (n=24) indicated that they would adopt DfAM at the stages conceptual design, embodiment design and detail design. 18.2% (n=20) at all four stages of the design process, while 17.3% (n=19) only at the conceptual design stage. 7.3% (n=8) would use DfAM respectively at embodiment design and embodiment design + detail design while 6.4% (n=7) at the conceptual design + embodiment design stages. 5.5% (N=6) would use DfAM at the brief setting and brief setting + conceptual design stages. 3.6% (n=4) in conceptual design and detail design. Only 1.8% (n=2) and 0.9% (n=1) would use it at brief setting + conceptual design + embodiment design and brief setting + embodiment design. When compared to question 23 where the detail design stage was the most frequently indicated stage, contrarily in this case, the concept design stage was the most indicated design stage. This result can be interpreted as recognition of the importance of introducing knowledge of AM as early as possible into the design process and particularly during idea generation.

Table 21: Stages of the design process in which DfAM knowledge is considered most suitable

Design stage	Frequency
‘Conceptual design’, ‘Embodiment design’ & ‘Detail design’	24
‘Brief setting’, ‘Conceptual design’, ‘Embodiment design’ & ‘Detail design’	20
‘Conceptual design’	19
‘Embodiment design’	8
‘Embodiment design’ & ‘Detail design’	8
‘Conceptual design’ & ‘Embodiment design’	7
‘Brief setting’	6
‘Brief setting’ & ‘Conceptual design’	6
‘Conceptual design’ & ‘Detail design’	4
‘Detail design’	4
‘Brief setting’, ‘Conceptual design’ & ‘Embodiment design’	2
‘Brief setting’ & ‘Embodiment design’	1

Utilisation of topology optimisation and generative design in DfAM

A similar pattern of responses resulted for both the utilisation of topology optimisation and generative design. Roughly half of our respondents stated that they have never used either topology optimisation (n=59, 53.6%) or generative design (n=52, 47.3%) in their practice. Roughly a third have used these tools occasionally, with topology optimisation being used *seldom* by 12.7% (n=14) of the participants and *sometimes* by 18.2% (n=20) and generative design being used *seldom* by 11.8% (n=13) and *sometimes* by 20.9% (n=23). The remaining participants, 11.8% for topology optimisation and 17.3% for generative design, utilised these tools on a more regular basis. Inside this group, generative design showed a slightly higher utilisation rate of 2.1 (*often* n=13, 11.8% and *almost always* n=6, 5.5%) compared to the utilisation rate of topology optimisation (*often* n=9, 8.2% and *almost always* n=4, 3.6%).

Table 22: the utilization of topology optimization and generative design tools

Category	Not at all	Slightly	Moderately	Very	Extremely				
	n	n	n	n	n	N/A	Mdn	IQR	Utilization
‘Generative design’	52	13	23	13	6	3	2	2	2.1
‘Topology optimization’	59	14	20	9	4	4	1	2	1.9

Type of information about DfAM required by the participants

The overall majority (n=95, 86.4%) of our sample stated that they would have benefited for more information regarding DfAM.

Concerning with the kind of information they would have liked to know, participants expressed a consistent interest in knowledge about materials (40.0%, n=44). This category included more specific information about material properties, material capabilities, materials available, materials limitations, comparison with materials used in conventional processes, results of testing, applications, materials cost, characteristics of new and multi-materials.

Information about process followed as the second most requested category (33.6%, n=37). In this category, the participants expressed their interest in knowing more about new technologies, process selection compared with conventional processes, process limitations, process capabilities, printing techniques, process performance, process requirements and process trade-offs, such for instance surface quality vs production time.

Design emerged as the third category (23.6%, n=26). This category indicated the need for information regarding different design aids such as design methods and software tools, design rules, design guidelines, design limits and design techniques. Some specific requests included design rules for detailed features, design rules for supports, design rules for surgical implants, impact of build orientation and layer thickness on features and mechanical properties, infill methods and weight reduction. Generative design and topology optimisation were included under design tools and software. These two were mentioned by four participants each but this result may have been influenced by the previous question.

Production cost was indicated by 12 participants (10.9%). These participants particularly requested more information on break-even point of a part, cost-benefit analysis and budgeting tools. A similar number of participants (n=11, 10.0%) expressed the need for more case studies, examples and best practices for understanding the potentialities of AM in real production.

The categories surface finish, machines, mechanical properties of the part, techniques, production time, tolerances, production volumes, metal additive and suppliers were indicated by less than 10 and more than 1 respondent. Surface finish included information about resolution, colours and post processing. Machines comprised advice about maintenance, optimisation, setup and available machines. Mechanical properties of the part concerned how to create strong and stiff components. Techniques included generic references to new techniques. Production time information concerned how to increase speed and reduce build time. Tolerances involved figures about accuracy and actual tolerances achievable by specific processes and machines. Production volumes concerned when AM is suitable for series production and for how many parts. Metal additive indicated the participants who asked for more info about metal AM and suppliers represented the need for information about suppliers and companies working in the field of AM.

Under the category *other* were included all the answers that did not fit into the previous categories or were difficult to interpret. Among these answers, the most interesting results were the suggestions made by two participants about the type of resources they would have found useful. The resources indicated were book, website and workshop.

Table 23: Type of information on DfAM required by the participants (n= 180 Types of information/n=110 respondents)

Category	Subcategory	Answers	Frequency
Materials			43
	Generic information about materials	'Materials', 'Materials', 'materials', 'materials', 'individual quirks in materials and specific machines', 'Materials', 'Materials', 'specific material regulate', 'Details about different and new printing materials', 'materials available', 'and raw materials for AM', 'About materials' and 'Material'	13
	Material properties	'material sheets', 'material specifications', 'advanced material character', 'Material properties', 'Material technical characteristics' and 'Material available, properties of them, relative costs, limitations of each',	6
	'New materials	'what are the technical limits and the new possible innovations', 'Details about different and new printing materials', 'Advances in materials', ''new', materials', available (metal alloys, etc.)', 'updated printer tech & material tech' and 'new materials'	6
	Mechanical properties of the materials	'Mechanical optical characteristics of the materials', 'How prototyping materials can best simulate manufacturing materials in terms of tolerance and physical strength' and 'Advances in materials, in particular mechanical strength & property comparison of materials compared with standard billet.'	3
	Materials capabilities	'Materials capabilities', 'I would like to know What capabilities and materials are available as well as how they compare to traditional injection moulded resins' and 'Material and strength capabilities'	3
	Materials available	'Materials availability' and 'Material available'	2
	Materials limitations	'Process and materials limitations' and 'Material available, properties of them, relative costs, limitations of each'	2
	Materials comparison	'objective material testing results and comparisons' and 'Particular mechanical strength & property comparison of materials compared with standard billet',	2
	Optical properties of the materials	'Mechanical optical characteristics of the materials'	1
	Fatigue & wear	'Fatigue and wear test data'	1
	Multi-material	'Multi-material AM'	1
	Materials testing results	'objective material testing results and comparisons'	1
	Materials applications	'Use of different materials'	1
	Materials cost	'Material available, properties of them, relative costs, limitations of each'	1
Process			37
	Emerging technologies	'Emerging technologies', 'the latest technologies', 'what are the technical limits and the new possible innovations', 'Information relating to advances in or new technology in this field', 'New available AM technologies. With a detailed technical explanation', 'Newest reliable technologies out there and their benefits/drawbacks', 'New developments', 'New technology', 'technology developments and applications', 'updated printer tech & material tech', 'New technology', 'New technology' and 'future technologies'	14
	Process selection – comparison	'Additive manufacturing has a range of different processes each of which has its advances and disadvantages. By know this information you can make an informed choice which process would be best for your products', 'Manufacturing decision support for process selection', 'I would like to know What capabilities and materials are available as well as how they compare to traditional injection moulded	6

		resins', 'Comparisons between methods. Realistic information about when to use and what to use', 'High level comparison matrix of technologies' and 'Performance vs. traditional manufacturing processes'	
	Process limitations	'Process and materials limitations', 'What are the technical limits and the new possible innovations', 'Additive manufacturing has a range of different processes each of which has its advances and disadvantages. By know this information you can make an informed choice which process would be best for your products', 'Newest reliable technologies out there and their benefits/drawbacks' and 'cons'	5
	Process capabilities	'Additive manufacturing has a range of different processes each of which has its advances and disadvantages. By know this information you can make an informed choice which process would be best for your products', 'Newest reliable technologies out there and their benefits/drawbacks', 'I would like to know What capabilities and materials are available as well as how they compare to traditional injection moulded resins', 'Pros' and 'benefits'	5
	Generic information about process	'working process' and 'process'	2
	Printing techniques	'print optimisation techniques' and 'Different printing strategies and techniques'	2
	Process performance	'process performance'	1
	Process specific requirements	'Process specific requirements'	1
	Process Trade-offs	'Trade-offs: cost, quality, appearance, etc.'	1
Design aids			29
	Design guidelines	'There is very little documented specific information on DfAM guidelines and post-processing', 'Design guidelines for optimization of results', 'Design guides', 'Process specific requirements/ guidelines for efficient manufacture (cost, time, labour etc.) – including consideration of build orientation and layer thickness and their impact on features and mechanical properties. I think this should always be considered after you have looked at and designed for the required function, adding as much value as possible in terms of performance, weight, assembly, aesthetics etc. Then choose the process and material and optimise that design for efficient manufacture.' and 'Design guidelines'	5
	Generative design	'generative design', 'generative design', 'Generative Design' and 'Generative design'	4
	Topology optimization	'topology optimization', 'Topology optimisation', 'topology optimization’ and 'Topology optimization'	4
	How to avoid support structures	'Overhanging length for each angle for which support is not required in different AM process' and 'Effective Support design'	2
	SolidWorks shortcuts	'SolidWorks shortcuts'	1
	Design rules	'design rules'	1
	Materials and Machines specific design rules	'Design rules for AM materials used in specific machines'	1
	Minimum wall thickness	'minimum thickness'	1
	Design rules for detailed features	'Specific details on rules for creating detailed features'	1
	Design rules for surgical implants	'Design rules for specific surgical implant applications (linked to clinical outcomes)',	1
	Design tools and software	'Design tools and software'	1
	Similar guideline to injection moulding	'A similar guideline to injection moulding process.'	1
	Build orientation and layer thickness impact on features and mechanical properties	'guidelines for efficient manufacture (cost, time, labour etc.) – including consideration of build orientation and layer thickness and their impact on features and mechanical properties'	1

	Design limits	'limits to design'	1
	Design techniques	'design techniques'	1
	Infill	'internal fill methods'	1
	Design aspects to optimize the process	'More information with respect to the design aspects to optimise manufacture if components linked to process.'	1
	Weight reduction	'weight reduction'	1
Production			19
	Production cost	'Production Cost', 'pricing', 'typical costs', 'working process & cost', 'budgeting tools', 'cost', 'Cost effectiveness', 'Cost-Benefit analysis', 'budgeting tools' and 'Part cost'	10
	Production time	'production time', 'Info about real manufacturing times.', 'lead times' and 'advances in print speed',	4
	Production volumes	'Large volumes production and additive manufacturing', 'When it can be used for low volume manufacture' and 'mass production use',	3
Price breaks		'Price breaks vs. other technologies' and 'Currently there is a fast development of decreasing costs, different in each method. Important to know, when "break even" will be achieved',	2
Case studies		'Case studies where it has been successfully employed for products similar to those I commonly encounter.', 'Use of AM in complete product/systems/services/experience examples of other designers/companies.', 'Best practices.', 'application', 'Case studies', 'best practices', 'complete developments showing the area where and why additive manufacturing was used', 'Examples, Experience reports, Case Studies', 'technology developments and applications', 'experience about the implementation in the design process' and 'uses in real production'	11
Surface finish			8
	Generic information on surface finish	'How to improve stiffness and surface appearance', 'Materials, strength, internal fill methods, finishes', 'finish', 'Surface quality' and 'Surface finish'	5
	Resolution	'resolution for different technologies' and 'I would like to know about the level of detail that is possible to be achieved.'	2
	Colour	'Surface finish & colour advances'	1
Machines			7
	Machines maintenance	'Machines maintenance' and 'while tools setup and maintenance information are harder to find'	2
	Machine optimization	'Optimisation of desktop FDM machines', and 'I also would like to know how to modify my current 3D printers and improve them'	2
	Generic information about machines	'individual quirks in materials and specific machines'	1
	Machines available	'printers available'	1
	Machine setup	'while tools setup and maintenance information are harder to find'	1
Techniques			5
	New techniques	'New and old techniques', 'new techniques' and 'new techniques'	3
	Generic information about techniques	'Tools and techniques' and 'news about technique',	2
Mechanical properties of the part			4
	Strength	'Materials, strength, internal fill methods, finishes', 'Material and strength capabilities' and 'making more accurate and/or stronger parts'	3
	Stiffness	'How to improve stiffness and surface appearance'	1
Tolerances		'Tolerances', 'Production tolerances', 'How prototyping materials can best simulate	4

	manufacturing materials in terms of tolerance and physical strength' and 'making more accurate and/or stronger parts',

Table 24: Generic information and N/A

Category	Answers	Frequency
'Don't know - Would like to know everything'	*'I wouldn't know until I come across something we couldn't figure out.', 'Generally open to all types of information', 'knowledge of the different offerings', 'Having as much as information possible', 'General News'* and *'News on process, machines, tools, speed, max. sizes,...'*	6
N/A		16

Table 25: Minor categories

Category	Answers	Frequency
'Metal additive'	'*metal additive' and 'Developments in metal RP.*''	2
''Suppliers'	'*suppliers and manufacturers we can work with.*' And '*location industries*'	2
'Resources for DfAM knowledge'	'*Most information is tacit, so a good source/book/website on DfAM and knowledge would be useful*' and '*Workshops*'	2
'Improving speed'	'*How to do it faster*'	1
'Medical or aerospace'	'*medical or aerospace*'	1
'Production design'	'*Production design*'	1
'Network Sharing Economy'	'*Network Sharing Economy*'	1
'Experimental process'	'*Experimental Processes*'	1
'Industrialisation'	'*Industrialisation*'	1
'Basics'	'*start from the basics*'	1
'Performance visualization'	'*Performance visualization*'	1
'DIY applications’	'*DIY applications*'	1
'Application Programming Interface'	'*Application Programming Interface for Additive Manufacturing*'	1
'Marketing'	'*Marketing*'	1
'Software support'	*'improved software support.*'	1

Prefered formats for accessing AM knowledge

Among the 22 different formats for accessing information on AM listed in the question, first person hands-on experience was the most preferred with a preference score equal to 4.1. Almost half of the participants (n=45, 47.4%) indicated that they extremely prefer this format. Online videos (preference score = 3.9) and talking with AM experts (preference score = 3.8) obtained also very high preference scores. Website and Sample piece/s both achieved 3.6. Seven other formats received a preference score between 3.4 and 3.0. These formats were library of products or components (preference score = 3.4), CAD software (preference score = 3.3), catalogue of case studies (preference score = 3.3), short training course (preference score = 3.3), images bank (preference score = 3.1), exhibition of products or components (preference score = 3.1) and blog (preference score = 3.0). 10 formats remained below the preference score of 3.0. Among these formats, decision support tool, wiki and handbook received scores of 2.9, 2.9 and 2.8 respectively. In the middle, between 2.7 and 2.5 there were 5 other formats such as makerspace (preference score = 2.7), long training course (preference score = 2.7), manual (preference score = 2.6), virtual or augmented reality (preference score = 2.6) and forum (preference score = 2.5). Finally, below 2.5, the formats textbook and smartphone app received the lowest preferences with 2.4 and 2.3 respectively. 19 participants indicated other formats. 4 of them specified *Conference tracts; a book like 'Process' by Jennifer Hudson, but solely focused on AM; datasheets with supporting test evidence* and *Case studies show market success/achievement by AM products*.

Interestingly, while first person hands-on experience and talking with experts are direct ways to collect information about AM and therefore can be preferred over other formats for the increased multi-sensorial involvement and interactivity, online videos are preferred at the same level.

Table 26: Participants' preference for different formats

Category	Not at all	Slightly	Moderately	Very	Extremely				
	n	n	n	n	n	N/A	Mdn	IQR	Preference
First person hands-on experience	4	5	10	31	45	15	4	1	4.1
Online videos	3	7	19	30	36	15	4	2	3.9
Talking with AM experts	4	12	19	28	32	15	4	2	3.8
Sample piece/s made with AM	6	9	26	28	26	15	4	2	3.6
Website	6	7	29	33	20	15	4	1	3.6
Library of products or components made with AM	8	13	19	39	16	15	4	1	3.4
CAD Software	12	13	26	20	24	15	3	3	3.3
Catalogue of case studies	10	11	31	25	18	15	3	1	3.3
Short training course	10	16	21	30	18	15	3		3.3
Images bank	10	16	30	25	14	15	3	2	3.2
Exhibition of products or components made with AM	13	16	30	21	15	15	3	2	3.1
Blog	14	18	28	24	11	15	3	2	3.0
Decision support tool	19	15	27	23	11	15	3	2	2.9
Wiki	16	20	30	20	9	15	3	2	2.9
Handbook	23	14	28	20	10	15	3	2	2.8
Makerspace	22	14	35	18	6	15	3	2	2.7
Long training course	26	19	19	23	8	15	3	3	2.7
Manual	21	21	30	19	4	15	3	1	2.6
Virtual or augmented reality	25	21	26	14	9	15	3	2	2.6
Forum	21	18	41	13	2	15	3	1	2.5
Textbook	31	20	26	12	6	15	2	2	2.4
Smartphone app	28	29	23	10	5	15	2	2	2.3
Other	75	6	11	1	1	16	1	0	1.4

Table 27: Comparison between the results of question Q22, Q26 and Q31

Sources of DfAM knowledge (Q22)	Usefulness (Q26)	Preference (Q31)
'Previous experience in Additive manufacturing'	'Personal experience'	'First person hands-on experience'
'Experimenting with AM technologies'	'Other products or components made with additive manufacturing'	'Online videos'
'Speaking with experts'	'Blogs'	'Talking with AM experts'
'Looking at how products are made'	'Expert tuition'	'Sample piece/s made with AM'
'Reading books'	'Manuals'	'Website'
'Surfing on the Internet'	'White papers produced by suppliers'	'Library of products or components made with AM'
'Attending a training course/s'	'Software based support tools'	'CAD Software'
'Visiting trade fairs'	'Training courses'	'Catalogue of case studies'
'Reading trade magazines'	'Wiki'	'Short training course'
'Other'	'Books'	'Images bank'
	'Trade fairs'	'Exhibition of products or components made with AM'
	'Magazine articles'	'Blog'
	'Bespoke company tools or methods'	'Decision support tool'
	'Journal papers'	'Wiki'
	‘Other’	'Handbook'
		'Makerspace'
		'Long training course'
	‘Speaking with experts and peers’	'Manual'
		'Virtual or augmented reality'
		'Forum'
		'Textbook'
		'Smartphone app'
		'Other'

Interest in participating in a Follow-up interview

30.9% of the respondents indicated their interest in continuing to participate in the research; while 34.5% expressed interest in remaining informed about the project.

Discussion

These results show that despite the hype and the excitement surrounding AM, a large proportion of practising designers have never designed end-use components for AM mainly because of cost, stakeholders' influences and perceived limitations. However, a small number of practitioners have designed end-use components for AM. The detailed questioning revealed that designers who have such experience developed it by designing low to medium production volume components for traditional industrial and product design sectors such as consumer goods, electronic goods and medical devices. They largely gained their DfAM knowledge by experiential learning and adopted AM because of its inherent capabilities. Taken together, these findings point towards the need for investigating and disseminating more DfAM knowledge in the design industry in future.

Designers' experiences in designing end use components for AM

Considering that the use of AM for prototyping is now an integral part of modern day design (Sass and Oxman 2006), the fact that our sample indicated they routinely use AM for prototyping is not surprising.

Whilst it is not as established as prototyping, the design of tooling, jigs and fixtures to be made with AM is also well established amongst designers. This confirms studies that have demonstrated the advantages of this approach (Rahmati 2014; Dippenaar and Schreve 2013; Rayegani et al. 2014; Chua, Leong, and Liu 2015).

A few studies have attempted to investigate the design of end-use components using AM as the production process. However, along with the findings of Dorrington et al (2016) our results confirm that this remains a very limited practice and a significant majority of our sample have not designed with this outcome in mind. Indeed, despite claiming to have used AM, only 23 participants (20.9%) completed the questions related to DfAM experience. Although a statistical generalisation is not possible, this figure is probably an overestimate compared to the overall population of industrial and product designers. The overall percentage of designers with experience in DfAM is very likely to be lower. In fact, the number of people who started the survey, but did not complete it reinforces this hypothesis and provides an approximate indication of this effect.

We are conscious that the language and terminology adopted in the survey might have influenced participation, as AM is possibly less widely recognised than the more common term 3D Printing. We aimed to address this in the introduction to the survey by stating that AM is considered synonymous with 3D Printing but it is possible that respondents may have abandoned the survey at this point. Another explanation that supports this hypothesis is given by self-selection bias (Wright 2005). Designers with more interest in the topic were more likely to complete the survey. Therefore, it can be concluded that for industrial and product designers, the design of end-use components for series production in AM is still a relatively niche phenomenon compared to prototyping or even to tooling. Few designers have had such experience and even for those, this appears to be an unusual activity.

Regarding the industrial sector, the main sectors cited by our participants were consumer goods, medical devices and consumer electronics. This may suggest that, while a large amount of current research is focused on highly technical fields, there are applications for series production in AM also in the traditional areas of industrial and product design. This seems to support the hypothesis that AM should be considered as a manufacturing choice for industrial and product designers providing there is sufficient design guidance to enable appropriate process selection based on functional and economic criteria.

The overall dimensions of the components produced in series using AM varied from 20 x 10 x 15 mm to 400 x 500 x 280 mm with a mean size of 144.3 x 116.3 x 63.5 mm. These can be considered the dimensions of small to medium size components. Interestingly, the dimension in the Z-axis is generally lower and 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 might also be a result of the difference in production time and cost between the horizontal and vertical axes (Singh, Rayegani, and Onwubolu 2014). A conclusion could be that a typical component for AM has small to medium size with flat and wide proportions.

The literature generally indicates that AM for plastics can be suitable for production volumes up to tens of thousands (Hopkinson and Dickens 2003a; Atzeni et al. 2010; Stucker 2011). However, the majority of the production volumes provided by our sample were between 11 and 1000, which is in agreement with the results reported by Karania & Kazmer (2007). A reason for this may be related to size. Atzeni et al. (2010) tested a small component (15.3 x 19.5 x 28.2mm), Karania & Kazmer (2007) a medium one (100 x 50 x 15 mm) and Hopkinson & Dickens (2003b) compared small (overall size 35 mm) and medium (overall size 210 mm) sized components. They concluded that AM processes are more suitable to series production of small parts and that there is an approximate factor of ten difference in production volumes between small and medium components. Therefore, an indirect strong correlation was expected between size and production volume. Surprisingly, the analysis did not reveal any significant statistical correlation between these two variables. This result is probably affected by the fact that the small size components in our sample do not present production volumes higher than 1000, even if higher volumes were theoretically possible (Saleh et al. 2004; Atzeni et al. 2010; Stucker 2011; Baumers et al. 2016). This could indicate that regardless of size, AM is generally used for low volume productions.

As expected, the most common material and process combinations for end use components were Material Extrusion with ABS and Powder Bed Fusion with Polyamide. For Material Extrusion with ABS this is probably due to the low cost of production, availability and good material properties. While for Powder Bed Fusion with Polyamide, the reasons are likely to be the combination of relative low cost (a result of high build capacity), good accuracy, good resolution and good material properties (Stucker 2011; Ruffo and Hague 2007). Additionally, vat photopolymerisation seems to be commonly adopted for series production. Despite the very high resolution, accuracy and surface finish, the literature considers this process suitable mainly for prototyping due to limited material properties and demanding post processing operations (Hague, Mansour, and Saleh 2004; Cotteleer 2014). Therefore, this result was unexpected. A possible explanation could be the recent development of materials better able to approximate the mechanical properties of engineering polymers (Chockalingam et al. 2008).

Reasons and limitations when designing end use components for series production in additive manufacturing

The main reasons for using AM provided by our participants are consistent with those of other studies. Low volumes (Stucker 2011), complex shape (Lipson 2011), shape manufacturability and customization (Lipson 2011) are the distinctive advantages of AM as compared to traditional processes (Baumers et al. 2016).

What is surprising is that the other main reasons such as cost and speed are generally considered limitations of AM rather than advantages (Ruffo, Tuck, and Hague 2006; Hopkinson and Dickens 2003b; Bourell, Leu, and Rosen 2009). 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 is low or the shape particularly complex to fabricate, AM is probably an economically viable alternative (Stucker 2011; Atzeni et al. 2010).

Likewise, speed should probably be interpreted inside the overall development process rather than only as AM build time. 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 (Achillas et al. 2015; Ford 2014).

Perhaps the most unexpected findings are the reasons that were indicated only once or twice. The majority of these reasons are similar to other positive characteristics of AM reported in the literature such as *confidentiality*, *constant feedback*, *easiness*, *short development time*, *lightweight*, *internal structure*, *no stock*, *organic shape* and *no need for tooling* (Dorrington, Bilbie and Begum 2016; Stucker 2011). However, other reasons highlight some unexpected and significant properties of AM such as *optical properties*, *suitability for implants*, *no need for aesthetic qualities*, *nano coating* and *cryogenic performance*. These reasons are seldom cited in the literature and they provide a glimpse of the diverse range of motivations that can lead to the selection of AM.

Finally, reasons such as *finishing*, *low post processing* and *precision* seem again to differ from the literature (Baumers et al. 2016). Although, with noticeable differences between dissimilar AM processes. Overall, AM techniques are still regarded as processes that provide low surface quality and low dimensional accuracy compared to conventional processes (Lee et al. 2014; Boschetto and Bottini 2016; Thompson et al. 2016). Therefore, components made in AM require laborious postprocessing to achieve an end user grade finish. This might indicate that general statements about AM characteristics may be misleading and that AM characteristics should be considered in relation to the requirements of the specific application.

Five main limitations for using AM for series production emerged from our survey. These reasons were cost, post processing, productivity, materials, build platform and accuracy.

The limitation cost seems to be a very interesting result since 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. The result shows that among this group of 9 participants, five mentioned their reason was complexity of shape, three stated the peculiar characteristics of SLS and one low volumes. Therefore, it can be argued that despite AM being considered expensive, designers selected it because of its unique capabilities. This might reflect that, although cost is a crucial factor for designers in materials and process selection, it is not a dominant driver in itself (Pedgley 2009).

As regards the other limitations such as post processing, productivity, materials, build platform, accuracy and surface finish; they seem to confirm those highlighted by previous studies (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 is an interesting perspective because it acknowledges the role DfAM knowledge as an enabler for exploiting AM capabilities.

Overall, the results of this section indicate the ‘relativity’ of AM advantages and limitations. If for example, in one specific application AM surface finish might not fulfil the design requirements, in another application this characteristic might be sufficient (e.g. ‘No need for aesthetic qualities’). Additionally, the reasons and limitations given in response to these questions provide an initial record of the possible motivations and limits for selecting AM as a production process. However, given the small sample (n=23) it is difficult to draw conclusive results on neither the exhaustiveness of this list nor the relative importance or frequency of these factors in design practice. Furthermore, these findings indicate that there are some contradictions between the reasons, the limitations and the acknowledged characteristics of AM. The survey was not able to provide in-depth insights about these contradictions and further studies were required to investigate these aspects.

The knowledge adopted in designing for AM

With few exceptions, there was a prevalence of detail design rules among the design aids indicated by our sample. This prominence of detail design rules over design principles, guidelines, tools or methodologies supports the idea that current DfAM knowledge is mainly limited to ensuring ‘printability’ in the late stages of the design process rather than supporting the exploitation of AM capabilities (Guo and Leu 2013) and the generation of innovative design solutions from the conceptual design stage.

Another important finding was the frequency of ‘Self-developed design guidance’ used for the design of the AM components. This can be explained in part by two concurring factors. First, it may confirm our assumption that there is a lack of readily available, formalised DfAM knowledge that designers can easily retrieve and use in their professional practice. This has been widely highlighted in recent studies (Lindemann and Koch 2016) and it reinforces the aim and scope of this research, while emphasizing the need for further investigation. However, a non-exclusive explanation could be that with AM it is easier for designers to self-develop design knowledge than it is with conventional manufacturing processes. AM has the ability to create three-dimensional objects directly from CAD data allowing designers to print out 3D representations of their designs that can be used for form, fit and functional testing during the design process (Stucker 2011). Additionally, the low cost and speed of the AM process means that designers can iteratively perfect their design through prototyping. So with AM, designers can directly engage with the production process and shape the final outcome (Karana, Pedgley, and Rognoli 2015) which is in all aspects identical to the final product (e.g. material, shape, colour, mechanical properties, etc.). This characteristic supports a continuous design and learning process that leads to the rapid development of expertise grounded on the relationship between materials, shape and process (Sass and Oxman 2006; Gerber and Carroll 2012). Therefore, 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 (Bettiol and Micelli 2014; Anderson 2010; Thompson et al. 2016).

A conflicting outcome also emerged between the adoption and rejection of injection moulding design guidelines (IMDG) when designing components for AM. Two participants declared that they followed the ‘same (design rules) as injection moulding’ while another, in remarkable contrast, declared ‘ignore injection moulding design considerations’. This contradiction is a result of the extreme flexibility of AM and its early application for prototyping, which have proved AM suitable for the fabrication of parts designed for injection moulding. The literature has generally supported the idea that to fully exploit AM capabilities for the production of end use components, design rules for conventional processes should be neglected (Hague, Mansour and Saleh 2003; Hague, Mansour and Saleh 2004). However, this contradiction might be an evidence of manufacturing-driven and function-driven design strategies proposed by Klahn, Leutenecker, & Meboldt (2015;

Leutenecker, Klahn, & Meboldt, 2015). They suggested that adopting IMDG reduces the risks associated with the market introduction of new products. Other explanations may be also plausible. For instance, one could be that designers are already familiar with the outcomes that they obtain by using IMDG with AM, because of their experience in prototyping. Additionally, IMGD are also more demanding and they can increase part quality and reliability in general (e.g. round corners generally reduce stress concentrations or thin uniform wall thickness reduces distortion in SLS); so, complying to them could be considered 'safe'. On the other hand, by following the design guidelines for conventional processes the capabilities of AM cannot be fully exploited, which is a profound limitation for the development of innovative solutions. The survey cannot provide conclusive evidence on this aspect. This contradiction requires further investigation to understand more in-depth when these two perspectives should be adopted.

Among the design aids, two were identified as design principles. 'Keep the part simple' is a widely-recognized design principle (Kristian Bjornard 2016; M. C. Yang 2005; Poli 2001). However, this is in contrast with much of the literature on DfAM, which emphasises the possibility of making complex shapes (Hague, Mansour and Saleh 2004; Hague et al. 2003; Hopkinson, Hague and Dickens 2006; Hague, Mansour and Saleh 2003; Ahuja, Karg and Schmidt 2015; Chryssolouris et al. 2012; Boyard et al. 2014). An interpretation could be that, even if complex geometries are possible, they might not always be an appropriate solution since complexity might interfere with other design requirements, for instance cleanability and maintenance. Moreover, although AM can generate very complex shapes, conversely it can equally well fabricate simple geometries. The principle 'part consolidation' is less ambiguous, since has been advocated as the one of the main advantages of AM in design. For instance, part consolidation can be used to reduce assembly operations, decrease material consumption and improve reliability (Tang, Yang and Zhao 2016; John Schmelzle et al. 2016; S. Yang, Tang and Zhao 2015; Hague, Mansour and Saleh 2004; S. Yang and Zhao 2015).

Two participants also specified 'build orientation' and 'incorporating structures to avoid stress build up during production'. Interestingly, these two aids can be interpreted as production characteristics rather than design characteristics. Even if the impact of build orientation in AM components is widely recognized (Cooke et al. 2011; Urbanic and Hedrick 2015); it has only recently been proposed to consider this characteristic in the design process (Leutenecker-Twelsiek, Klahn, and Meboldt 2016). For instance, in conventional processes, designers prepare a formalised description of the dimensional, geometrical and qualitative requirements of the component (e.g. CAD or engineering drawings) as the final output. They should be aware of the limitations of the technology, but specialised design engineers will develop it further according to requirements the final design and the associated tooling. These two results instead may show that in AM, design and production are closer than in conventional processes involving fewer intermediaries; or that in AM the production characteristics (e.g. build orientation) are more interrelated to the aesthetic and physical properties of the part than in conventional processes. However, other equally plausible explanations could be the lack of established design standards (Ameta et al. 2015) or the lack of professional figures that translate design requirements into production parameters.

Finally, other design aids were mentioned such as FEA, collaborations with engineers and design rules for orthotics design. FEA was interpreted as Finite Element Analysis, which could show the use of software for the geometrical optimisation of the components. Collaboration with engineers is probably related to acquiring and using knowledge from experts in AM. While design rules for orthotics design probably relates to the personalisation of medical devices, which may not be directly related to AM.

The approaches adopted to gather DfAM knowledge provide a further confirmation of the tacit experiential nature of the design knowledge adopted to design end use components for AM. In fact, the approaches indicated by over half of the participants were previous experience in AM, experimenting with AM technologies, speaking with experts and looking at how products are made. This may add additional evidence of the lack of available formalised DfAM knowledge (to practicing designers) (Li, Wu and Myant 2016) as shown by the design aids adopted. However, it could also signify a general preference of designers for tacit over explicit knowledge. This preference has been highlighted by other studies (Evans 2015; Pradel and Previtali 2012).

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 starting from the conceptual design stage. representing the recognition of the importance of introducing DfAM knowledge as early as possible into the design process to exploit AM capabilities fully. This confirms from a practitioners' perspective, the conclusions of previous studies that highlighted the lack of DfAM knowledge and aids targeted at the conceptual design stage (Laverne and Segonds 2014; Guo and Leu 2013; Doubrovski, Verlinden, and Horvath 2012; Rias et al. 2016).

Although, our sample is too small to provide a complete overview, these answers seem to demonstrate that the design knowledge surrounding AM 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. The sources used for gathering DfAM knowledge provide further indication of this. All the approaches that involved non-formalised knowledge were used by at least half of our sample. On the contrary, approaches that involved formalised knowledge were utilised by roughly a quarter of the sample. Finally, designers recognised the opportunity of adopting DfAM in the early stages of the design process.

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

Among the participants who have never designed for AM, cost resulted as the main reason for not using AM in series production with more than a third of the participants explicitly indicating it. This was to a certain extent expected since cost was also the main factor for designers who have experienced DfAM and for the literature (Ford 2014). 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 should be considered along with it. For instance, if cost is the main factor for not using AM, this is probably due to the fact that most participants design components for higher volumes than those suitable for AM (Baumers et al. 2016; Lindemann and Koch 2016); therefore, generally opting for other cheaper processes.

Two other factors mentioned consistently by our sample, 'has never been required' and 'clients', shed additional insights on the adoption of AM for series production. These factors may indicate that there is a form of inertia in the adoption of AM. This is consistent with a long tradition of research that has found diffusion to be slow for many technologies (Rogers 1995; Livshits and Macgee 2006). Additionally, it may confirm the influence of clients in designers' material and process selection (Crilly, Moultrie & Clarkson, 2009; Pedgley, 2009) and their role as active actors for innovation diffusion in design.

A large portion of reasons included well-known technological limitations of AM. Among those, significant factors were mechanical properties, speed, surface finishing, production volume, material performance, accuracy, quality, reliability, aesthetics, durability and limited available materials. These factors are consistent with the technological limitations of AM identified by previous studies (Baumers et al. 2016; Ford 2014; Gao et al. 2015; Oropallo and Piegl 2016; Dimitrov et al. 2014; Boschetto, Giordano and Veniali 2013; Huang et al. 2013; Boschetto and Bottini 2014) and taken together they may reflect that practicing designers are aware of those limitations.

Another main factor ‘lack of knowledge’ is self-explanatory. A portion of our sample acknowledges a deficiency of information regarding AM and consequently this limitation constitutes a barrier for the selection of AM as a production process. The need for upskilling workforce and supporting design tools and methodologies that aid design for AM has been identified (Manteil and Elsey 2016; Li, Wu, and Myant 2016; AM working group 2015; Quarshie et al. 2012; Industrial and Regional Valorization of FoF Additive Manufacturing Projects 2014). This result highlights how this need is also perceived by design practitioners.

Accessibility, technical support and supplier availability are other interesting factors. Pedgley suggested that the options in materials and processes that designers employed in in-house manufacturing companies are constrained by convenience (Pedgley 2009). For institutions, it is generally easier to utilise processes that are already available compared to other processes due to financial, time or knowledge factors. This might indicate that although AM could theoretically be recognized as the most suitable production solution, in practice in-house available processes or trusted suppliers might be preferred.

There are some reasons that have been highlighted in the literature, but little evidence has been found in the survey. Some examples of these were standards, post processing and size. For instance, standards have been highlighted as one of the main barriers for the adoption of AM in series production (Ford 2014). However, it was only mentioned once in the survey. This may indicate that standards might not be one of the more critical barriers for adopting AM for industrial and product designers.

There is also some evidence that AM is still considered as a prototyping technology. The reasons ‘not ready for series production’ and ‘perception’ seems to indicate this.

These reasons provide many insights on the current barriers to the adoption of AM for series production. They match the main technological limitations of AM observed in earlier studies. However, some factors show that these barriers are not only technical. Future research effort should investigate these behavioural aspects and particularly the practitioners and consumers’ acceptance of AM.

Limitations of the study

Given the non-probabilistic nature of the study, the main limitation of the study is the limited generalisation of the findings. However, the aims were rather to explore the phenomenon rather than to test any specific hypotheses. In this respect, this contribution clarifies some aspects of the topic and uncovers new paths for future studies. The limited number of participants with DfAM experience (n=23) has a negative influence on overall impact of the findings, especially in relation to the relative importance of the answers in the open-ended questions. Although the survey provides a good understanding of the application of DfAM in professional practice, the inherent limitation of the instrument did not allow us to explore the relationship between certain aspects of the topics in depth.

Incongruences in the answers given by our respondents were also noticed. For instance, when participants had to indicate the material and AM technology, in three cases participants indicated a non-existing material-technology combination (e.g. ABS + VAT photopolymerization and polyamide powder + Direct Energy Deposition). This may indicate the presence of errors in the answers. This error may influence some results, especially those related to the designers' experiences due to the relatively low number of respondents (n=23), although, in those cases a more qualitative approach to the analysis was adopted. This approach was consistent with the aim of the study. Moreover, incongruences in these responses were easily identified because of rich data and the limited entries. For the sections with a high number of respondents (>70), potential errors did not significantly affect the overall results.

Conclusions

- Our population was largely designers (product and industrial), from the UK, Europe and North America. They have generally between 1 to 10 years design experience and they work mainly for design consultancies in the consumer goods, medical devices, industrial machinery and consumer electronics sectors.
- The large majority of our sample has never designed end-user products or components for AM.

Experience in DfAM

- The typical size of components produced in series in AM varies from 10 x 10 x 7 mm to 400 x 500 x 280 mm. However, the mean size was 138.7 x 111.8 x 61.2 mm. the size in the Z-axis is generally half of the size along the X-axis.
- The typical total production volumes for the end-user components made in AM are between 11 to 1000 pieces.
- Material Extrusion, Powder Bed Fusion and VAT photopolymerisation seem to be the most used AM processes to produce end-user components in plastics.
- Polyamide and ABS seems to be the materials frequently most used.
- The main reasons for using AM were low volume, complex shape, speed, cost, shape manufacturability and customisation.
- The main limitations of using AM for series production were cost, post processing, productivity, materials, build platform and accuracy.
- There is conflict between either adopting or disregarding injection moulding guidelines when designing components made in AM.
- Personal experience is acknowledged as the most valuable approach to gathering DfAM knowledge. Other products or components made with AM seem also to be important elements as well as expert tuition and training courses.

Knowledge about DfAM

- Cost is the main perceived reasons for not using AM in production. Interestingly, many designers have never designed for AM because AM has never been required.
- Although DfAM seems to be currently adopted mainly during the detail design stage, the conceptual design stage is recognised as the most suitable stage for introducing DfAM knowledge into the design process.
- Topology optimisation and generative design are not widely utilised by designers.
- Materials, process, design, production and surface finish are the five types of information designers would like to know about DfAM.
- First person hands-on experience, online videos, talking with AM experts, websites and sample pieces made with AM are the formats that designers prefer for accessing information about designing for AM.

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