A framework for mapping design for additive manufacturing knowledge for industrial and product design

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ABSTRACT

Design for Additive Manufacturing (DfAM) is a growing field of enquiry. Over the past few years, the scientific community has begun to explore this topic to provide a basis for supporting professional design practice. However, current knowledge is still largely fragmented, difficult to access and inconsistent in language and presentation. This paper seeks to collate and organise this dispersed but growing body of knowledge, using a single and coherent conceptual framework. The framework is based on a generic design process model and consists of five parts: Conceptual design, Embodiment design, Detail design and Process planning and Process selection. 81 articles on DfAM are mapped onto the framework to provide, for the first time, a clear summary of the state of the art across the whole design process. Nine directions for the future of DfAM research are then proposed.

Introduction

Additive Manufacturing (AM), also referred to as 3D printing, is enabling a revolution in the way products are designed and produced (Hague, Mansour, and Saleh 2004; Junk and Tränkle 2011; Ahuja, Karg, and Schmidt 2015; Gao et al. 2015). However, significant barriers must be overcome if these technologies are to be widely used for mainstream serial manufacture (Royal Academy of Engineering 2013; Wohlers 2015). Perhaps the most significant hurdle is a lack of knowledge amongst designers on how to design components that take full advantage of these new technologies. Indeed, the codification of insights regarding design rules, principles, best practices and standards has been identified as a major limiting factor in the uptake of AM by designers (Thomas 2009; Meisel and Williams 2013; Schmelzle et al. 2016). Without appropriate design knowledge, it is not possible to fully exploit the potential of AM and enable the transition from Rapid Prototyping (RP) to mainstream end-use part production (Adam and Zimmer 2015; Ahuja, Karg, and Schmidt 2015). As with any manufacturing process, it is not possible to design effective components unless the subtleties of the process are understood. This may mean that designers will need to discard

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some hard-learnt design rules for conventional manufacturing techniques and acquire a new mindset targeted explicitly towards AM.

There has been a recent increase in academic attention on Design for AM (DfAM). Recent review papers have aimed to synthesise key issues (Gibson, Rosen, and Stucker 2010; Yang and Zhao 2015; Kumke, Watschke, and Vietor 2016; Thompson et al. 2016). Whilst these papers effectively review current work they have either presented highly technical, process specific design rules (e.g. Yang and Zhao 2015) or have offered qualitative guidelines at a heuristic level (e.g. Gibson, Rosen, and Stucker 2010). Neither approach provides a complete overview of current DfAM knowledge or methods that have been developed to support industrial and product design practice.

With industrial and product designers in mind, this paper provides a framework for the growing body of knowledge on DfAM and seeks to offer a coherent and consistent overview of the current research landscape. Starting from the literature, DfAM knowledge has been mapped against a model of the design process to propose an original framework. The framework aims to assist the design research community in developing new and more comprehensive DfAM knowledge and ultimately more effective design guidance that can inform design educators and practicing designers.

Section 2 introduces previous studies. Section 3 describes the method adopted for collecting the resources. Section 4 discusses the dimensions for mapping DfAM knowledge. Section 5 presents the framework and the mapping of current DfAM knowledge. Finally, Section 6 addresses current limitations and proposes areas for future research.

Previous attempts to categorise DfAM knowledge

In 2010, Gibson, Rosen and Stucker presented an extensive overview of AM design capabilities and CAD tools with examples of applications in industrial design. Later, Rosen (2014) presented a further review of different design principles and strategies that might be applied to AM. The review proposed four fundamental principles of DfAM, several 'design characteristics' and four innovative 'design strategies'. Rosen (2014) noted the extremely specialised nature of the available AM design methods and tools. He also predicted that research into DfAM would take two distinct directions, creativity tools for exploiting AM capabilities mainly tailored for industrial designers and engineering design tools for supporting product functionality.

In 2015, Yang and Zhao (2015) presented a comprehensive critical review of the impact of AM in design theory and methodology. In the first part of the paper, the authors proposed three categories of studies regarding DfAM; design considerations for manufacturing, assembly and performance. In the second part, they presented three categories of AM-related design methods; general design guidelines, modified conventional design theories and methodologies for AM and Design for AM. The authors also presented three design aids, a generic design framework that integrated a set of functional-driven design activities, a method for simultaneously synthesising process knowledge and functional requirements and an analytic model for supporting the design process. The paper provided a systematic review of relevant literature on DfAM. However, the focus of the analysis and the proposed future developments were narrowly centred on mechanical engineering rather than a more generalised perspective on industrial or product design.

Kumke, Watschke, and Vietor (2016) also revised previous studies on DfAM and suggested two categories of DfAM aids according to their main purpose and application. These two categories were 'DfAM in the strict sense' and 'DfAM in the broad sense'. DfAM in the 'strict sense' included approaches intended for the core design process, such as: 'AM design rules' for ensuring AM-producible parts; and 'AM design potentials' for taking advantage of AM capabilities. DfAM in the 'broad sense' were the methods not directly related to the design process itself but to selection of parts/applications and manufacturability analysis. Moreover, the authors integrated the 'DfAM in the strict sense' approaches into a design process model based on VDI 2221. The review highlighted the fragmentation of previous studies and the lack of an overall design framework for DfAM. In addition, they enumerated further secondary limitations regarding the limited validity of design rules, their focus only on a single optimisation objective and the lack of methods aimed at fostering innovative design solutions. While the review was comprehensive, as with previous studies, the focus remained on engineering design and prescriptive approaches.

Thompson et al. (2016) presented an extensive review of DfAM studies describing terminology, design opportunities, constrains and cost factors of AM. They concluded that DfAM is still 'in its infancy' and there is a need for better guidelines for DfAM. They suggest that future research should address this gap, and proposed a 'functional surface approach' to component design (Ponche et al. 2012) as well as noting that DfAM must also extend to encompass the broader production system. They noted that effective designer education is critical in bridging this gap. However, although the paper provides a comprehensive overview of current developments in DfAM, with many helpful illustrative examples, the multiple ideas introduced are not unified through a common framework or language.

Finally, several different authors have considered how different design rules, principles and heuristics might map onto a generic design process model. Rosen (2014) was the first to propose the potential benefits of mapping/categorising studies of DfAM, although he did not enact this recommendation. Laverne and Segonds (2014) considered the results of nine individual studies and mapped these against a simplified version of the Pahl et al. design process (2007). The Laverne and Segonds categorisation exposed a distinct lack of DfAM tools and methods targeted at the early stages of the design process. They also highlighted the tendency for research in this area to focus on the detailed design of specific geometrical features (e.g. overhangs, wall thickness etc.). The paper was original in its approach but was limited in its breadth of content. However, it successfully demonstrated the potential value of mapping current work onto a design process model as a means of building a framework aimed at designers.

Our approach builds upon these studies by expanding the breath of the resources considered and by integrating an additional dimension concerning the typology of design guidance (i.e. principles, heuristics, guidelines and rules). This provides another layer for classifying and understanding the knowledge developed around this topic. As we have uncovered in a previous study, whilst there is a good deal of structural or mechanical engineering-based litertature available (Pradel, Zhu, et al. 2018), practising product and industrial designers still have very little awareness or understanding of DfAM knowledge. This has profound implications on the identification of when AM is suitable manufacturing route, how to exploit AM opportunities and mitigate its limitations through good design. Therefore, this framework aims to support designers and researchers in navigating this

emerging field and retrieving relevant knowledge for designing end use components and products produced with AM.

Method

This paper proposes an original and critical analysis of the state-of-the-art in DfAM based on a systematic literature review. We adapted Kitchenham and Charters's (2007) systematic literature review approach comprised of three distinct activities:

- the formulation of the review protocol, including search terms (keywords/phrases), inclusion and exclusion criteria;
- the collection of relevant documents;
- analysis and synthesis of the remaining studies in a framework
- (Pradel, Zhu, et al. 2018) The review protocol explicitly identified the basis of the search, in terms of keywords or phrases. This included the identification of inclusion/exclusion criteria, the search strategy, methods for data organisation and the approach to be used for analysis/synthesis.

The search covered research articles (from journals and published conference proceedings), theses, white papers and blogs written in English and published after January 1995. The specific search terms used to identify all possible articles are summarised in Table 1. The specific phrase 'design for additive manufacturing' was used to ensure searches identified relevant documents as opposed to those with any of the words in any sequence, which would have resulted in numerous irrelevant results. A range of databases were searched, with specificity (where available) regarding the use of the phrase in either title, abstract or keywords. The use of alternative databases resulted in a considerable number of duplicates, which also helped ensure that the search was comprehensive. In addition to the academic databases, we included a broader search using Google Scholar, recognising that the topic also has significant professional practitioner interest.

This initial search yielded 734 articles (Table 1). Using Endnote (a bibliography management tool) 194 duplicate studies were removed, resulting in a total of 540 articles.

For each of the remaining articles, the titles and abstracts were reviewed to eliminate irrelevant articles. A broad range of criteria was used and articles that were eliminated included those related to . . .

Table 1. Summary of search queries on March 2016.

| Database	Query	No. of articles
Scopus	TITLE-ABS-KEY ('Design for Additive Manufacturing')	54
Science direct	('Design for Additive Manufacturing')	43
Web of science	TS = ('Design for Additive Manufacturing')	80
Emerald Insight	'Design for Additive Manufacturing'	11
IEEE Xplore	'Design for Additive Manufacturing'	2
ProQuest	'Design for Additive Manufacturing'	68
Google scholar	'Design for Additive Manufacturing'	438
Google	'Design for Additive Manufacturing'	38
	TOTAL	734

- specific medical, biological or textile applications and hence not providing insight into general industrial / product design;
- specific materials development;
- technological development of the production process;
- the economics of AM only;
- metals processing within AM;
- topology optimisation as a late design stage activity;
- tooling or quality issues;
- mechanical performance only;

172 articles remained and a further 30 were eliminated from the study after reading abstracts. If there was any doubt regarding the relevance of the article, then it carried to the second stage.

The citations of the remaining 142 articles were examined to identify whether any important studies had been missed in the initial search. This 'snowballing' approach (Jalali and Wohlin 2012) generated an additional 45 articles, resulting in 187 articles for detailed review.

Considering that the research was aimed at the needs of mainstream industrial and product design, as opposed to highly constrained mechanical, structural or safety critical engineering design, the articles were examined in detail to determine their relevance and significance.

Following this detailed review, a further 106 articles were removed from the list, based on the criteria listed above, as well as their 'quality' in terms of rigour or reliability. At the
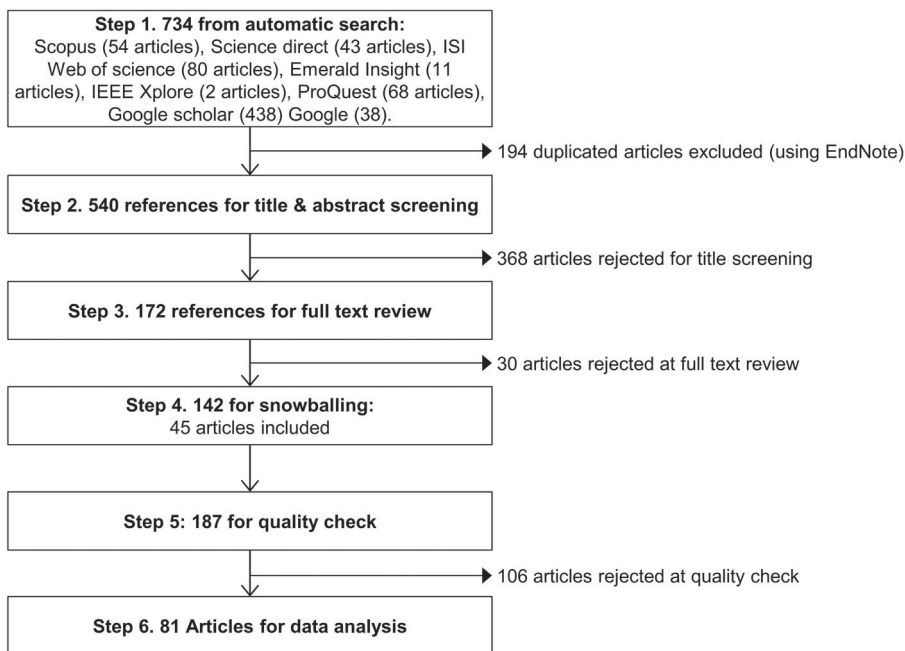
Figure 1. Summary of literature review strategy.

end of this process, 81 studies remained (see appendix 1 or https://d4am.blogspot.co.uk/ for a full list) and these formed the basis of the critical review.

The search strategy described above is illustrated in Figure 1.

Dimensions for mapping DfAM knowledge

Type and date of publications

The majority of the studies included in the review were published in journals and conferences that belong to the most cited publication sources in AM providing confidence in this review and its overall quality. Most of the studies were peer-reviewed journal articles (40 articles, 48%), followed by peer reviewed conference papers (27 articles, 33%). Ten documents (12%) were white papers published from industry and the remaining items (6%) comprised a book, three theses and a standard.

We noted that from 1999 to 2007 very little was published (13 articles in total). However, from 2012 around 10 articles were released every year, demonstrating a rapidly growing knowledge base in this area and highlighting the timeliness of this review.

Validation methods

Table 2 provides a classification of the 81 studies based on the research methods used to investigate DfAM (Glass, Vessey, and Ramesh 2002; Fu, Yang, and Wood 2015, 2016). It is useful to note that 19 of the studies did not report the methods used and that the dominant approach for approximately half of the sample were case studies. The large number of case studies / experimental studies and the absence of more in-depth qualitative studies such as interviews or ethnography further supported the premise that little is known about DfAM in current industrial practice.

Point of application in the design process

Our approach builds upon the work of both Kumke, Watschke, and Vietor (2016) and Laverne and Segonds (2014), using a simplified design process (Figure 2), consisting of four main phases: brief setting; conceptual design; embodiment design; and detail design, along with the parallel process of material and process selection (Ashby 2011). These stages are

Table 2. Description of validation approaches.

Research method	Description	Number of articles
Case study	Studies included into this category validated the proposed design aid developing of one or more components or products	37
Experiment	Studies using laboratory experiments and statistical analysis are included in this category	14
Review	Studies that analysis the existing studies, typically with the aim of exploring the domain and understanding the concepts, fall into this category	5
Design experiment	Studies in which the design aid has been evaluated through a design activity carried out by other designers in a controlled environment	6
Survey	Studies that fall into this category have used interviews or questionnaires to survey practices, opinions and so on from a (large) population	1
Not mentioned	Studies that do not mention any methods either implicitly or explicitly are sorted here	19
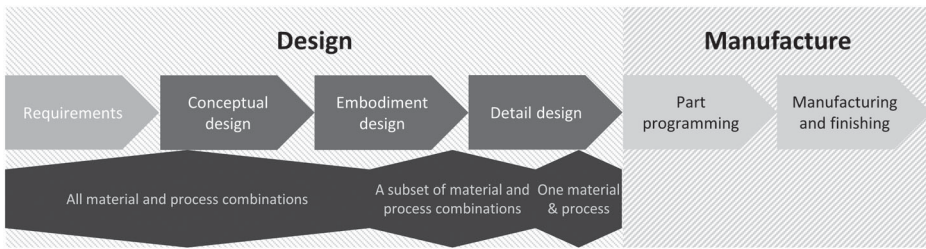
Figure 2. A simple design process model.

consistent with several generic design process models (e.g. Asimow 1962; French 1985; Ashby 2011; Pahl et al. 2007; Dieter and Schmidt 2012). However, we acknowledge that in reality design practice may start at different points of the design process depending on the brief and the type of project. Also process selection, which theoretically starts with all the possible materials and processes, may also be initially constrained. This constraint may depend by both internal and external factors such as the machines and technologies available in the company or the network of potential suppliers.

The process in Figure 2 was used as a basis for mapping the key design rules, guidelines or insights identified in each of the 81 papers.

Table 3 summarises the 'focus' of the studies in terms of the design process stages. Greatest attention has been given to embodiment and detail design, with fewer papers addressing the conceptual design stage.

Typology of design guidance

The DfAM knowledge that emerged from the literature was classified according to the typologies of design guidance presented in Table 4. These typologies are adapted from Fu, Yang, and Wood (2015).

In categorising evidence from publications, we make a novel and very important distinction between guidance that might influence the *design* and guidance that relates to the *definition of the parameters of the production process*. Thus, we set a specific criterion to separate 'design guidance' from 'manufacturing process guidance'. Our definition of 'design guidance' is that it should influence the shape of the part (i.e. its form or its geometry). Rules relating to the parameters of the manufacturing process (e.g. build speed) are therefore viewed as process guidelines and they are not considered part of DfAM. However, it is still important that designers are aware of these issues, even if they do not have a direct impact on part form/shape/geometry.

Table 3. DfAM methods at different stages of the design process.

| Research method	Number of articles
Conceptual design	17
Embodiment design	26
Detail design	27
Process selection	16
General design process	9

Table 4. DfAM typologies.

Typology	Definition
Design heuristics	Design heuristics are context-dependent directives that support the design process by increasing the chances of reaching rapidly and efficiently a satisfactory, but not necessarily optimal solution. Design heuristics are generally not explicitly validated, but based on intuition, tacit knowledge or experiential understanding.
Design principles	Design principles are high-level directions derived inductively from extensive experience and/or empirical evidence. They can provide indications on how to design efficiently and/or exploit AM capabilities. Because of their highly abstract nature principles can be difficult to apply in practice; however, they are less restrictive than other typologies and therefore they be suitable for supporting creative activities such as concept generation.
Design guidelines	Design guidelines are context-dependent directives that provide design process direction to increase the chance of reaching a successful solution. Their validity is proven by extensive experience and/or empirical evidence. Design guidelines are generally less abstract and more applicable than principles, but also less general and more restrictive.
Design rules	Design rules provide knowledge where the relationship between cause and effect is well known and they produce predictable and reliable results. They are generally drawn from quantitative experiments or from the analysis of an extensive number of cases. Generally, they are employed at the detail design stage to refine the shape/form or to optimise geometrical features, (e.g. precisely define fillets, radii, wall thicknesses etc.). Validity is limited to a specific material and process combination.
Process guidelines	Process guidelines are information on how to perform the AM / 3D Printing process and achieve the desired part requirements. They define machine parameters and post-processing operations. This type of information belongs to the domain of manufacturing engineering and the designer does generally not have direct control over it. However, awareness of process guidelines will benefit the design process.
Specifications	Specifications are information for the AM / 3D printing process about the characteristics of the part that can be neither expressed through shape nor modelled in CAD. In traditional manufacturing, such characteristics are tolerances, roughness and finishing (e.g. colour). In AM, other characteristics can be specified without affecting the CAD geometry. Some examples are infill (percentage and shape), resolution (layer thickness), part orientation, mechanical properties of the material (e.g. e-material), etc. Specifications are generally codified by international standards and communicated through engineering drawings.
Process selection tools	Process selection tools are decision-making aids for selecting the appropriate processes. They can be distinguished in two categories, tools that support the selection between AM and conventional manufacturing and tools that support the selection between the different AM processes. Their nature can be both qualitative (for the early stages of the design process) and quantitative (for the later stages where more detail information of the part is available).

Building the framework

This section consists of six sub-sections presenting evidence relevant to each element of the design and manufacturing process. At the end of each section, the key issues are summarised and the framework extended to incorporate them. The framework will be built 'backwards' from manufacture, back through the design process. This presents the framework moving from specific details, through to more conceptual challenges.

Manufacture and post processing

Whilst AM processes can produce near net-shape components, there remain instances where post-processing operations are needed, and these have an influence on the design decisions taken. As a general design goal, these post-processing operations should be minimised (Ayre 2014). These are summarised in Figure 3.
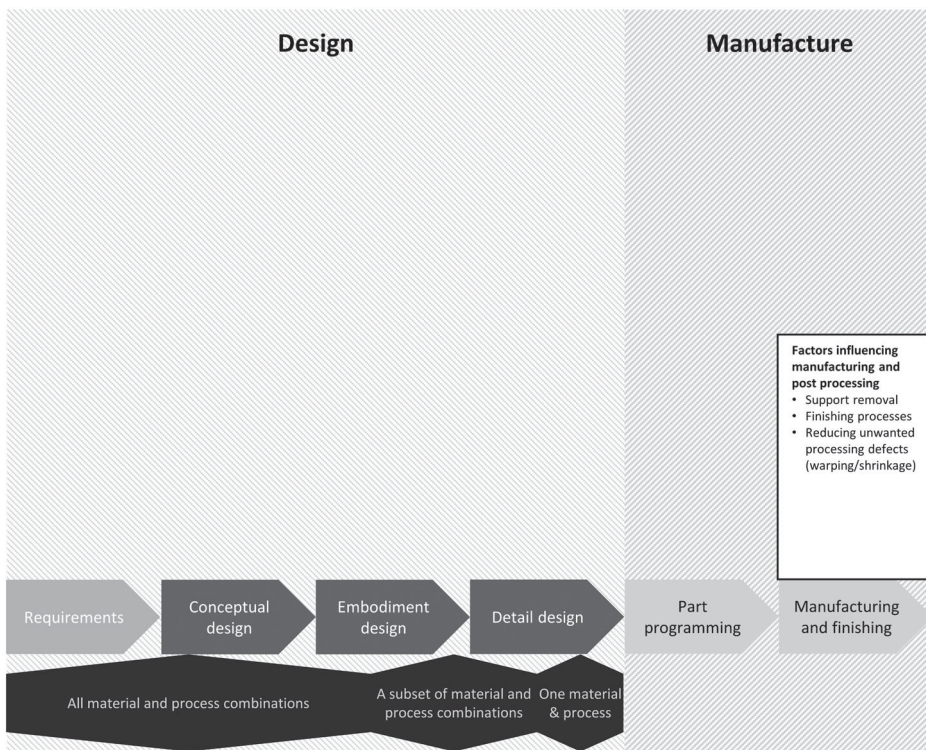
Figure 3. Manufacture & post processing guidelines.

Support removal

Designers quickly learn that components with overhangs, undercuts or suspended features (e.g. Kannan 2017) cannot be printed unless these features are supported (e.g. Fused Deposition Modelling and Stereolithography). All supports need to be removed after printing and represents wasted energy, time and material (Strano et al. 2013). Light supports can be easily removed by hand or might be dissolved in water/solvent, whilst some supports require machining operations (Ayre 2014). Removal of support material also has the potential to damage the component, especially if wall thicknesses are too small to provide sufficient strength (Kannan 2017). Designers might include a 'shear edge' near supports to enable them to be quickly and efficiently removed (Klahn, Leutenecker, and Meboldt 2015). A challenge is the removal of unused build material and or support structures from internal cavities and specific design features need to be included to enable this (ISO/ASTM 2015).

Finishing processes

AM produced components often need additional processing, including excess powder removal, surface finish improvement, machining, thermal treatment and coatings (ISO/ASTM 2015). Surface finish of AM parts can be poor due to material properties and stepped layering over sloping or curved surfaces. Abrasion, chemical treatments and coatings can be used for smoothing on some surfaces.

Reducing unwanted processing defects

Designers should be aware of unwanted defects, such as curl, warping and shrinkage and their impact on final dimensions and geometry (Zaragoza-Siqueiros and Medellín-Castillo 2014). Permanent or removable support structures might prevent or reduce the impact of some of these defects. Heuristic rules are often applied, such as avoiding large flat down facing surfaces (Ayre 2014; Samperi 2014; ISO/ASTM 2015) or including support ribs (Kannan 2013; Ayre 2014).

Design issues that relate to component manufacture are represented in Figure 3.

Process planning and optimisation

Process planning and optimisation is the point at which, once a part is designed, the detailed process parameters are determined in order to produce the component as intended. A typical output would be a 'process sheet' for each component that specifies each sequential step in the manufacturing process, materials used, any tooling and clarity on the specific production machines to be used. At this point, a reliable estimate of production time, cost and material usage is possible (Scallan 2003).

For conventional processes, process planning is normally a 'manufacturing engineering' task, and not a direct concern of the industrial designer (Dieter and Schmidt 2012). As AM processes produce near net-shape components, planning requirements are light compared to conventionally produced components. However, some significant planning issues will have an impact on the design of a component. The following key issues emerge in the literature (see the appendix for a detailed analysis). Although presented independently, they are all related. For example, Zaragoza-Siqueiros and Medellín-Castillo (2014) presented design rules for support structures, cavities and overhangs in relation to part orientations and tool-path planning. Process issues are summarised in Figure 4.

Build orientation

The structural properties of AM parts are anisotropic (it is build direction dependent) due to the layer-by-layer nature of the fabrication processes. Build orientation thus has a strong influence on the mechanical strength of parts under different loading conditions, especially parts made using Fused Deposition Modelling (FDM) (Ulu et al. 2015). Build orientation also affects dimensional tolerances and surface finish, in parts produced using FDM, Selective Laser Sintering (SLS) and Selective Laser Melting (SLM). For example, Snyder et al. (2015) found that for parts made using SLM, features in the vertical direction had the highest surface quality but also the lowest concentricity, circularity and total run-out. Elsbrock (2014) provided basic guidelines to show how to modify a design from a stair-stepped surface requiring supports to a smooth curve without supports. Thus, whilst build orientation does not specifically affect the underlying component form / shape / geometry, the impact on functionality and performance can be significant (Teitelbaum, Schmidt, and Goaer 2009; Thomas 2009) and needs to be understood by the designer.

Support optimisation

Components with features such as undercuts and overhangs need support structures during the printing process (RedEye 2014). The design of features to minimise the need for support is covered in the 'detailed design' section. However, the extent of the supporting
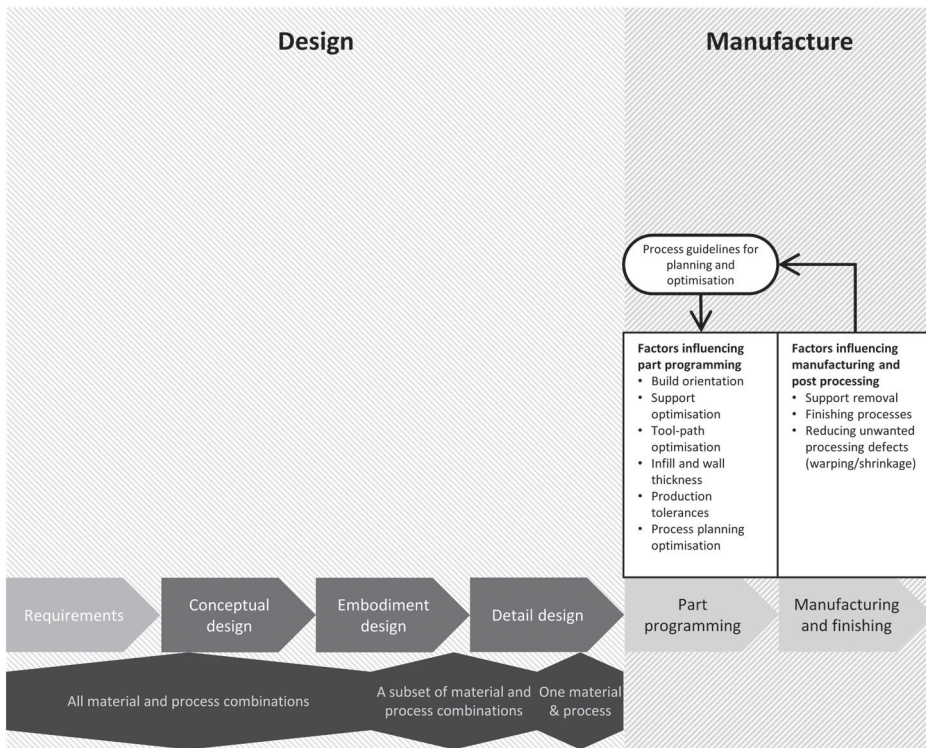
Figure 4. Process guidelines.

material used is often a variable that can be modified at the production stage. Software to generate the print file will normally identify the support structures needed automatically, with operator intervention limited to adjustments (e.g. from light to dense support). Strano et al. (2013) reported an optimisation method to minimise the volume of support structures by generating graded cellular supports, which can reduce support volume by around 45%.

Tool-path optimisation

For any given geometry, it is possible for the 'tool' (for example the print head in FDM) to follow a variety of paths, at a variety of speeds to build the component. Variation in the tool-path can have an impact on part curl or warping and thus structural viability. Fornasini and Schmidt (2015) demonstrated that choice of deposition paths could have an impact on plastic performance and tensile strength. Jin, Li, and Gao (2013) and Ponche et al. (2012) both explored how to optimise the tool path of the print head, and the impact this has on component characteristics. Such optimisation has the potential to improve the physical properties of components as well as reducing overall build time.

Infill and wall thickness

Thin walls can result in components that buckle and have poor strength. Thicker walls will increase build time and cost. Gorguluarslan et al. (2015) developed a model to simulate the impact of changes to material thickness, shrinkages, air gaps and strut lengths on final component properties. They highlighted the inherent uncertainties in the production quality

of FDM produced parts, dependent upon critical process parameters. The choice of wall thickness is both geometry and application dependent, and its importance for FDM parts is highlighted in the design guidelines by RedEye (2014) who suggest the minimum wall thicknesses that advisable depending on material (e.g. ABS, Nylon) and layer height. They provide general guidance that to reduce buckling, the thickness of vertical walls should be at least twice the layer thickness.

Production tolerances

For series production, geometric dimensioning and tolerancing (GD&T) are critical issues, as components must reliably fit into larger assemblies. AM machine specifications typically quantify 'resolution', but not the likely dimensional precision of the manufactured part. To date, there is very little research in this area and thus there is little guidance available to designers. Ameta et al. (2015) investigated the impact on GD&T of a range of variables, including build direction, layer thickness, and scan/track directions. Whitney and Moultrie (2016) also measured dimensional variations resulting from different process settings and concluded that variations in wall thickness and infill can have a significant impact. The variation in dimensional precision and the lack of reliable data presents a major challenge for designers wishing to create parts with reliable repeatability. This is a key area where further work is needed.

Process planning optimisation

Several models, tools or methods have been developed to analyse the suitability of parts (and features) for AM or which seek to optimise process parameters (e.g. Filippi and Cristofolini 2007; Zhang and Bernard 2014; Zhou et al. 2014; Kerbrat, Mognol, and Hascoët 2011). These methods seek to ensure that the specific process parameters selected are suitable for the component being produced and often indicate how features might be modified to enable efficient production. Ranjan, Samant, and Anand (2015) proposed a 'producibility index' for components to be made using Direct Metal Laser Sintering (DMLS) to quantitatively evaluate the manufacturability of a designed part in the selected build orientation, looking at sharp corners, small holes, thin regions, cusps, support structure and surface area contacting support. This method aims to modify the design iteratively until no problematic features remain.

Design issues that relate to process planning are represented in Figure 4.

Detail design

At the detail design stage, all the decisions regarding the product and its components are optimised. These decisions cover aspects such as dimensions, tolerances, surface properties, materials and manufacturing processes for individual components as well as the product (Pahl et al. 2007; Ashby and Johnson 2009; Dieter and Schmidt 2012). In this section, we summarise design rules that can be used to optimise and refine features at the detail design stage. Issues that emerge from the literature include feature size, feature shape, supports and post-processing consideration.

Feature size

There are a growing number of studies that have investigated the capabilities of AM processes in printing different features, resulting in a set of rules regarding wall thickness,

hole size, feature length, feature depth and corner radii (e.g. Sells and Bowyer 2007; Shelley 2013; Ayre 2014; Adam and Zimmer 2015; Materialise 2016). Adam and Zimmer (2014, 2015; Adam, Zimmer, and Müller 2014) developed a method to establish design rules for different AM processes (i.e. SLS, SLM and FDM) where a part is treated as a number of standard elements (e.g. wall thicknesses, gap heights, length), element transitions and aggregated structures and varied these until test prints failed to obtain threshold values. Sells and Bowyer (2007) and Shelley (2013) provided information on how to design detailed features for FDM such as cylindrical fits, integral springs, avoid overhangs, and minimum feature sizes. Urbanic and Hedrick (2015) investigated the design rules for building large and complex components in FDM to identify the minimum wall thickness and dimensions of self-supporting overhangs. Seepersad et al. (2012) also investigated the limiting feature sizes for different types of feature to establish a designer's guide for dimensioning and tolerancing SLS parts. Govett et al. (2012) extended Seepersad et al.'s (2012) work to develop SLS design rules to determine the 'finest' features that might be produced. In the white paper by EOS GmbH (2014), the suggested maximum and/or minimum dimensions for laser sintering of texts, thin walls, pins, gaps and holes are documented. Kannan (2013) suggested a checklist to assess the detail design of the product, to ensure designers think about the maximum part size (to fit the desired AM system), minimum wall thickness, rigidity, faces requiring support, minimum printable feature size, ribs to reinforce thin walls, minimum hole diameter and corner radius. Thomas (2009) developed a set of feature-based detail design rules for SLM in relation to geometry and material properties for a range of features including overhangs, wall-thickness, slot-width, hole-diameter, radii and surface-roughness as a function of orientation, self-supporting holes and shrinkage. Finally, Teitelbaum, Schmidt, and Goaer (2009) used a simulation technique to model the FDM process to propose basic design guidelines for optimising part height, overhangs, holes and orientations.

Feature shape

Certain specific features must be avoided if a part is to be producible. For example, sharp inner edges that make removal of support structures (e.g. powder) difficult. Rounded and blunted edges are generally more desirable (Adam and Zimmer 2014). In addition, sharp edges also introduce detrimental stress concentrations and thus, fillet radii are advised, including at the root of threads (RedEye 2014). Kranz, Herzog, and Emmelmann (2015) experimentally derived guidelines for the printing of thin walls (SLM), bars and bores in relation to part orientation, position and size, covering a wide range of prismatic features including cavities, walls, bores, gaps, cylinders, overhangs and support structures. In addition to academic research, companies such as 3D Systems (2016) and EOS GmbH (2014) have published a range of SLS design rules for features such as hinges, threads and chains. Materialise (2016) has developed design rules for wall thickness, internal and external supports and clearances for interlocking mechanisms by taking into consideration, printing accuracy, surface roughness and anisotropy. Stratasys Direct Inc. (2015) also provided extensive detail design rules for FDM including, in addition to the above-mentioned features, shrinkage, warping, pins, threads, undercut fillets, living hinges, text, finishing and secondary operations. Ayre (2014) presented a list of design rules for DMLS, including thread designs, self-support angles, support structures and removal. In contrast with Hague, Mansour, and Saleh (2004), Ayre (2014) suggested maintaining thin and uniform wall thickness.

Eliminate features needing support

Components requiring significant support are costlier to manufacture (Strano et al. 2013). As a result, design guidance generally focuses on minimising the impact of overhangs to reduce the level of support structures needed (e.g. Hietikko 2014; Schmelzle et al. 2016). This may be through decisions on printing orientation, or by designing features to be inherently strong in the build direction. The most commonly cited rules are the '45° rule' whereby any overhanging surfaces should be at a minimum of 45° to the horizontal and limits to the length of overhangs (e.g. Adam and Zimmer 2015; Fernandez-Vicente, Canyada, and Conejero 2015). This value is supported by some experimental evidence. For example, Zaragoza-Siqueiros and Medellín-Castillo (2014) presented generic design guidelines for overhangs and support material removal. Enclosed volumes or cavities are thus generally to be avoided and any features needing support should be as small as possible to reduce potential damage to the printed part during support removal.

Adding excess material to enable post-processing operations

Post-processing is required for almost all 3D printed parts and there can be benefits in understanding this during detail design. For example, where a metal AM component needs machining to improve surface quality, additional material should be added (Elsbrock 2014). For plastic components with thin walls and quasi-hollow in-fill (e.g. FDM), holes cannot be added to the part post-process as once the outer wall is penetrated there is insufficient material inside. Thus, material may be added in locations where drilling may be needed.
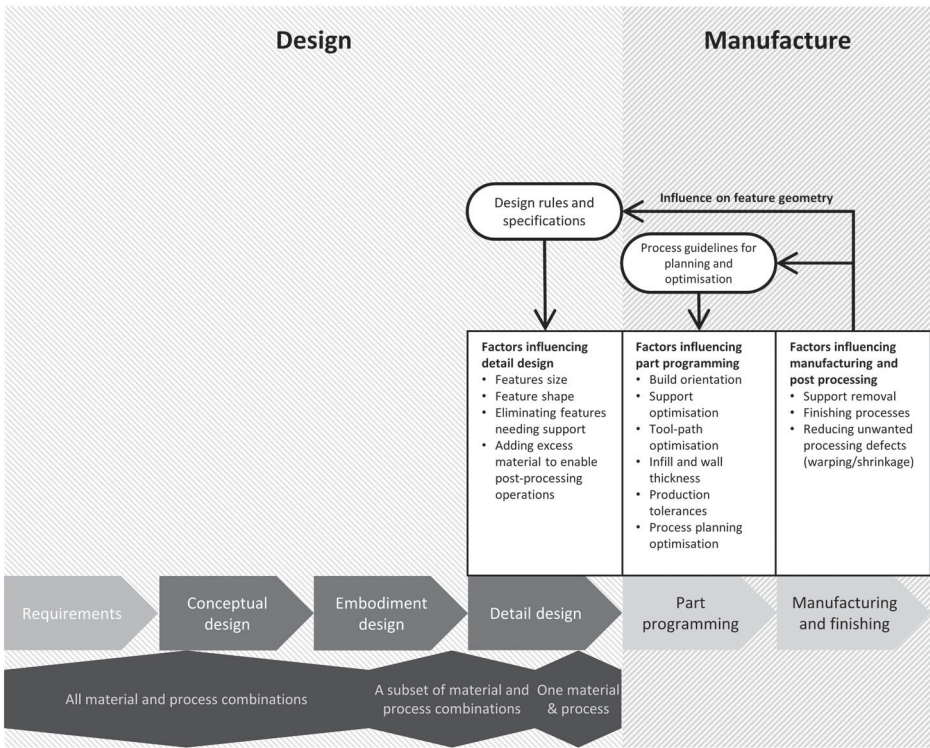
Figure 5. DfAM guidance for detail design.
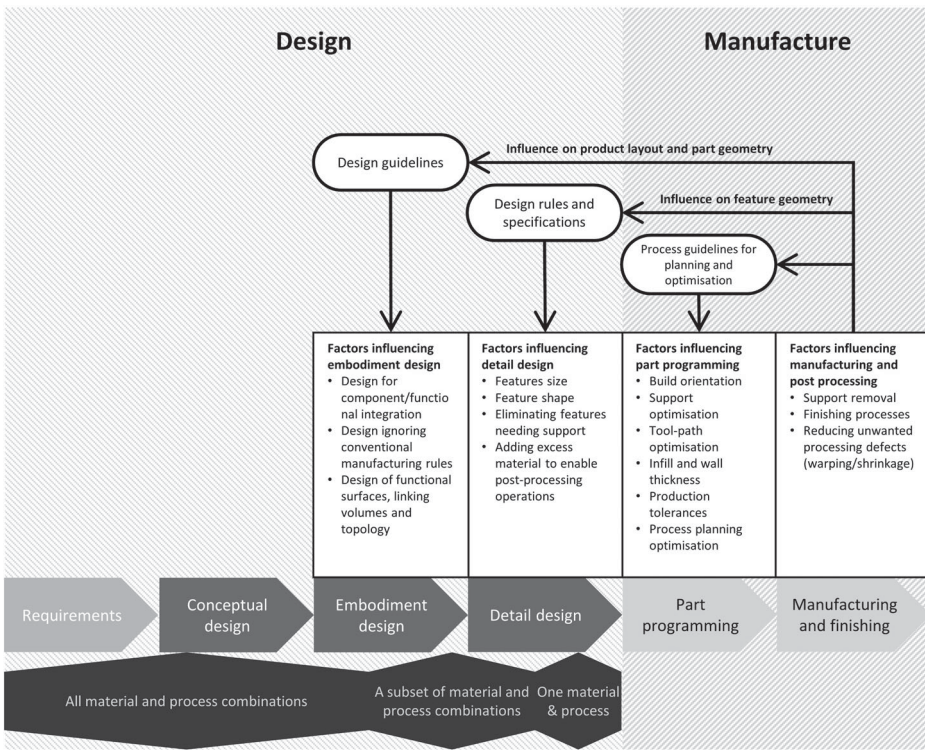
Figure 6. DfAM guidance for embodiment design.

Design issues that relate to detail design are captured in the framework, as shown in Figure 5.

Embodiment design

In embodiment design, the promising design ideas conceived during the concept design stage are further developed to a greater level of detail (Pahl et al. 2007; Cross 2008). At this stage, critical decisions regarding production processes and component form are resolved.

AM offers designers a range of 'potentials' (ISO/ASTM 2015), including weight reduction, use of internal structures, topology optimisation, component integration and integrated mechanisms. Much of the prior work provides examples of assembly/component 'redesign' to demonstrate the impact that designing for AM could make (e.g. Atzeni et al. 2010; Klahn, Leutenecker, and Meboldt 2014). In this subsection, we examined research that provides insight into how AM as a production process might be considered during embodiment design. In general, these approaches seek to optimise the overall design through reducing part count and reducing material content in the remaining parts. Key design approaches are highlighted in Figure 6.

Design for component/functional integration

Hague, Campbell, and Dickens (2003) noted that to take advantage of AM, designers should integrate a number of simple parts to create a single component with greater inherent

complexity. Indeed, the ability to produce complex components is often cited as a key benefit of AM. However, this introduces new design challenges. For example, there may be a knock-on effect on assembly or maintenance. Furthermore, the increased geometrical complexity will also result in increased build time and production cost, which is undesirable for volume production using AM (Pradel, Zhu, et al. 2018). Indeed, this is one specific topic where the general view that 'anything can be made' is at odds with design guidance which seeks to ensure parts can be efficiently made.

A number of methods for combining components have been proposed. Zhou et al. (2014) developed an approach that starts with an analysis of the primitive geometry and how it relates to the design constraints and component functionality. They subsequently applied optimisation methods to remove redundant material. Schmelzle et al. (2016) redesigned a hydraulic manifold, consisting of 17 pieces, into a single part, realising 60% and 53% reductions in weight and height, respectively. The new manifold also included specific features to enable some machining processes. As with Zhou et al. (2014), they first sought to define the boundaries and fundamental geometry of the system before subsequently applying optimisation approaches.

Design ignoring conventional manufacturing rules

Many leading thinkers promote AM as enabling designers to 'be free from all design constraints' (e.g. Rosen 2014). The implication of this perspective is that designers might ignore the constraints imposed by awareness of conventional design for manufacturing rules that might be applied to other processes. Thus, new forms are enabled that could not otherwise be produced. However; conventional design rules may be beneficial also when designing for AM. Klahn, Leutenecker, and Meboldt (2015) and Leutenecker, Klahn, and Meboldt (2015) conducted an experiment to compare the design outcomes depending on whether designers sought to accommodate conventional design rules or whether they ignored them. They observed that although the components designed were similar, by adopting design rules for conventional production technologies, the transition to volume production (using these processes) was simpler. Pradel, Zhu, et al. (2018) also showed that conventional design rules applied to AM may offer other advantages such as improving the component quality and reducing the effort in designing AM components.

Design of functional surfaces, linking volumes and topology optimisation

A common theme in design optimisation is to focus attention on the 'functional surfaces', which provide the necessary features and geometry to make a component work. With appropriate constraints (e.g. forces), it is then possible to link these features with material, often using computational methods to develop or identify an optimal solution (e.g. Ponche et al. 2012; Vayre, Vignat, and Villeneuve 2012; Yang, Tang, and Zhao 2015). It can be seen from the examples above that topology optimisation methods are growing in use as an approach to reducing excess material. These methods typically result in complex geometries, with internal channels that are virtually impossible to be manufactured by conventional manufacturing methods and thus are especially suitable for AM production. Part consolidation and topology optimisation are thus often considered in unison (Rodrigue and Rivette 2010). Watts and Hague (2006) conducted a preliminary investigation on a genetic algorithm based on topology optimisation to create heterogeneous part structures that exhibit uniform stress distributions. These optimisation approaches often

rely on stress analysis methods to ensure maximum component strength with minimum material (e.g. Shea, Fadel.). Whilst this provides a logical approach for engineers to take for safety critical weight reduction in aerospace for example, this level of optimisation may be unnecessary for typical components in industrial / product design. The risk of relying on computational means is that the designer does not instinctively begin to apply the same rationale. Design issues that relate to embodiment design are captured in the framework, as shown in Figure 6.

Conceptual design

Conceptual design is an initial stage of the design process in which a large number of design solutions are conceived, explored and evaluated upon a specific set of requirements or statements (Smith and Eppinger 1997; Cross 2008; Ashby 2011). Studies that provide tools or methodologies for supporting AM at the conceptual design stage are reviewed in this sub-section, which is organised in two main parts; namely DfAM for concept generation and concept selection, respectively. There is a distinct lack of prior work that seeks to provide designers with guidance during the generation of conceptual designs that take advantage of the benefits of AM. The few studies that exist tend not to have the proposed methods validated by practicing designers. There is also a lack of attention given to understanding how designers currently design products and components with AM in mind. The framework showing the methods for generating new concepts are depicted in Figure 7.
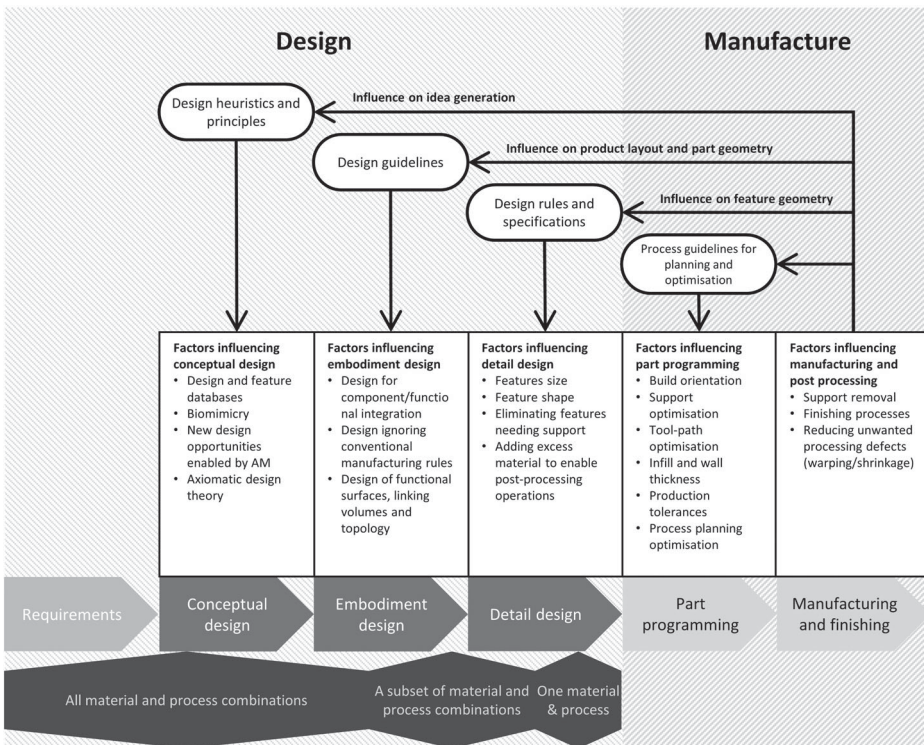

Figure 7. DfAM guidance for conceptual design.

Design and feature database

With the growth of designs available online, Maidin, Campbell, and Pei (2012) developed a design 'feature database', which provides a diverse collection of products, designed for AM. Building on this work, Doubrovski, Verlinden, and Horvath (2012) proposed a wiki, an online sharing platform, for the collection and distribution of design experience and examples of AM applications amongst product designers (in an educational setting). Recently, Kumke et al. (2017) proposed an interactive system for AM design potentials coupled with physical artifacts. These studies demonstrated the effectiveness of databases of design solutions that might form a starting point for a new design.

Biomimicry

In 2007, Rosen (2007) proposed a design tool that aimed to 'reverse engineer biological systems', to help designers search for new solutions based on the working principles of biological systems. The underpinning logic was that AM production tools are an enabler to produce complex and organic components inspired by nature.

New design opportunities enabled by AM

Many authors have commented on the new 'design potential' offered by AM (e.g. Comb 2010; Gibson, Rosen, and Stucker 2010; Ponche et al. 2012). The result is a set of 'heuristic principles', which are generic and abstract in their nature. For example, Ponche et al. (2012) compared the design potentialities of AM with those of injection moulding and reported five potentials of AM, including production of complex components without increase of cost, removal of geometrical limitation, use of multi-materials, part customisation and customer-driven design. Ponche et al.'s (2012) paper was highly significant as it marked the first attempt to define AM opportunities for design. Although, these proposed heuristic benefits of AM were not evaluated empirically they continue to be influential. Similarly, Comb (2010) proposed five design guidelines, namely 'forget design for manufacturability', focusing on function, iterate, refine the design and 'question tradition'. Comb also proposed that designers should make it feature rich, rethink wall thickness, consolidate or segment, fill the envelope and ignore the details. These heuristic principles can provide a starting point for conceptual design and foster creativity, but their generic or abstract nature means that they may also be difficult to apply in a pragmatic sense.

Axiomatic design theory

Salonitis (2016) proposed a framework based on an axiomatic design theory, which can assess design ideas in the conceptual design phase by taking AM capabilities and limitations into consideration. The axiomatic design method addresses customer needs in terms of product functions to derive design parameters. The core of the framework is the decomposition of the design space into four domains i.e. customer, functional, physical and process. The functional requirements are shown in the functional domain, based on which the material and mechanical properties (in the physical domain) and the attributes of the process variables (in the process domain) are developed for manufacturing the product with the required functions. Thus, the AM characteristics are essentially considered in the conceptual stage for fulfilling the functional requirements. Design guidelines collected from

the published literature as well as practitioners are integrated in the physical and process domains to assist designers to decide process variables.

Material and process selection

Material and process selection tools for AM can be classified into two types. The first type aims to provide methods and tools for selecting the most appropriate material and related manufacturing process between AM and conventional processes. The second type only focuses on developing tools and methods for choosing the most appropriate material and process amongst AM technologies. This subsection provides a review on the first type of the process selection research.

Approaches for selecting between AM and conventional materials and processes

Different authors have proposed a range of different factors for determining whether AM might be a suitable alternative to conventional manufacturing processes. These factors include:

- Customisation / individualisation (Conner et al. 2014; Klahn, Leutenecker, and Meboldt 2014)
- Complexity of geometry and dimensional precision (Conner et al. 2014)
- Anticipated production volume (Conner et al. 2014)
- 'Integrated' design or part consolidation (Klahn, Leutenecker, and Meboldt 2014)
- Efficient / Lightweight design (Klahn, Leutenecker, and Meboldt 2014)
- Process cost comparison (Zhu et al. 2017)

Conner et al. (2014) concluded that components which are of low complexity, low customisation and high production volume less suitable for AM production. (Zhu et al. 2017) compared the costs of producing different components using both AM and also injection moulding to identify the tipping point at which conventional production methods become economically viable.

Both Zhou et al. (2014) and Lindemann et al. (2015) have proposed approaches which aim to evaluate the suitability of components for production using AM. Zhou's model evaluated a component's geometry to establish the technical and economic feasibility of producing parts using AM. Lindemann et al developed a matrix for evaluating designs on four dimensions: geometry, assembly, material and post-processing. They designed the matrix to be adaptable to the needs of different industries, such as aerospace, car industries and medical applications.

The standard entitled 'Standard Practice – Guide for Design for Additive Manufacturing' (ISO/ASTM 2015), also focuses on the technical elements of a component as a basis for process selection, including: material selection; surface and geometrical considerations; and static and dynamic physical properties.

Recognising the complexities of these production decisions, Munguía et al. (2010) developed an expert system comprising around 500 rules, which aims to enable designers to assess the possibility of using AM as a final manufacturing route. Based on the ranking of the design requirements and input parameters, different AM technologies are compared and the most appropriate one is then suggested.

Approaches for selecting between AM materials and processes

One of the first tools for AM process selection was developed by Bibb et al. (1999), focusing specifically on AM as a means of rapid prototyping. This knowledge based tool provided guidance based on data on part geometry, process capability, production volume and the physical properties of the components. The outputs indicated whether specific AM technologies were suitable, capable or incapable.

Other authors have subsequently developed different models for either selecting or prioritising different AM technologies, encompassing a range of criteria:

- Part size and Geometry (e.g. Armillotta 2008; Vinodh, Nagaraj, and Girubha 2014, (Smith and Rennie 2010))
- Process capability (e.g. Vinodh, Nagaraj, and Girubha 2014)
- Accuracy (e. g. Byun and Lee 2005; Kim and Oh 2008; Zhang, Xu, and Bernard 2014)
- Surface roughness (e. g. Byun and Lee 2005; Kim and Oh 2008)
- Material properties, such as strength (e. g. Byun and Lee 2005)
- Part cost (e. g. Byun and Lee 2005)
- Buid time or production rate (e. g. Byun and Lee 2005; Armillotta 2008; Kim and Oh 2008; Vinodh, Nagaraj, and Girubha 2014; Zhang, Xu, and Bernard 2014)
- Quantity (e.g. Armillotta 2008)
- Material cost (e.g. Kim and Oh 2008)

Kim and Oh (2008) developed some specific recommendations for process selection based on the material properties of different AM processes (including Stereolithography, Fuse Deposition Modelling, Material Jetting, Selective Laser Sintering, Binder Jetting, and and Layer Object Manufacturing). For example, Stereolithography is most suitable for parts demanding high hardness and accuracy but poor surface roughness. In contrast, Selective Laser Sintering is appropriate for highest production speed. Fuse deposition modelling is suitable for parts with high impact strength.

Figure 8 captures these elements in DfAM framework. This framework provides an overall view of the entire design process together with detailed considerations in each design stage that needs to be considered when designing a product specifically for AM.

Limitations and future directions in DfAM studies

The previous section has presented and categorised the different DfAM guidance available today. In this section, we present the characteristics and limitations of current DfAM knowledge and propose future research directions.

Different design knowledge for different designers

In the DfAM research to date, no studies have investigated the kind and level of DfAM knowledge required by the different actors in the design process. If we consider the opportunity to produce lightweight structures, the ability to define the internal density of a component to achieve lightweight (e.g. Cadogan, George, and Winkler 1994) can inspire concept generation (Maidin, Campbell, and Pei 2012; Doubrovski, Verlinden, and Geraedts 2016) and / or inform process selection (Klahn, Leutenecker, and Meboldt 2014; Lindemann
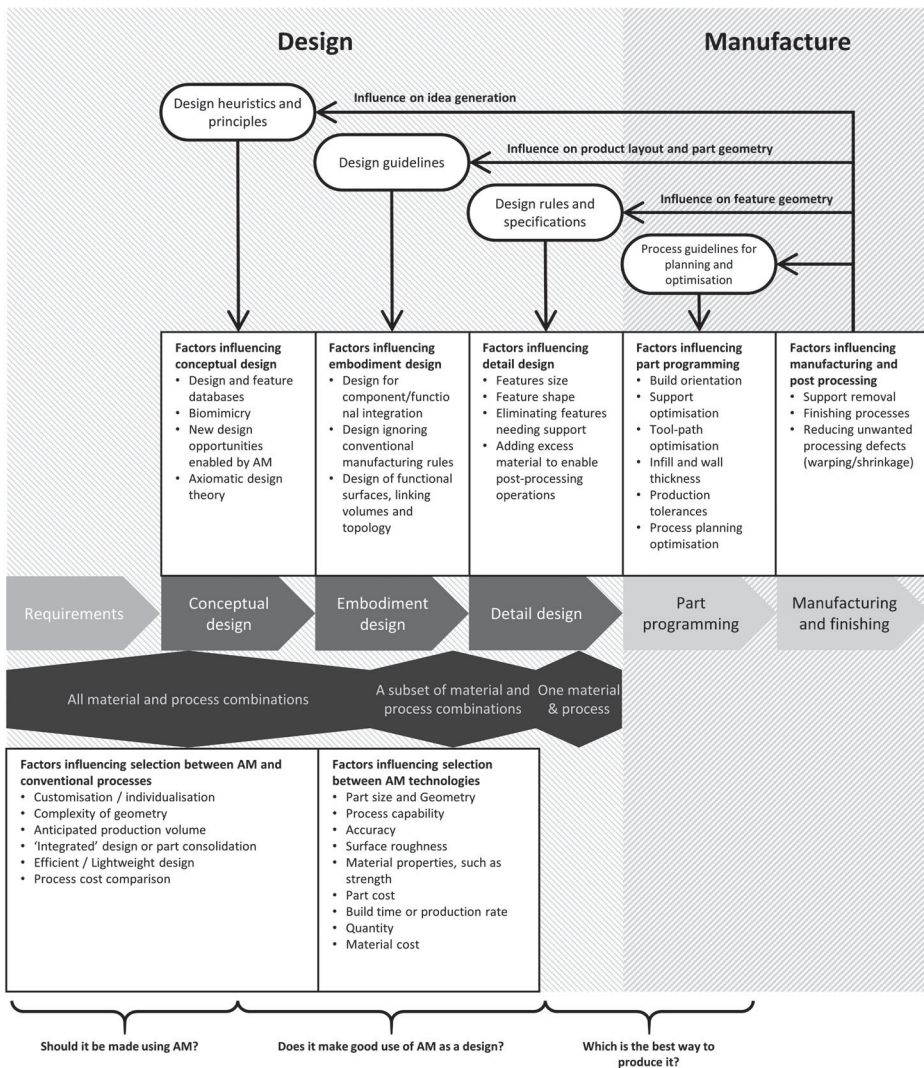
Figure 8. The framework for design for additive manufacturing knowledge.

et al. 2015). However, when the design idea is embodied, lightweight is realised by specifying which areas should be denser or sparser to withstand specified forces. This could be achieved through changes to form (shape) by adopting design tools such as topology optimisation (e.g. Rezaie et al. 2013; Alzahrani 2014; Asadpoure and Valdevit 2015; Cheng et al. 2015; Gaynor 2015; Zegard and Paulino 2016) or by controlling how the AM machine constructs the layers. For instance, in FDM this could be realised by defining the characteristics of the material deposition at the point of initiating the build at the machine, usually referred to an 'in fill' (Stratasys 2015). Therefore, the design knowledge on lightweight structures could be applied through form (changing the shape in CAD) during concept generation or it could be specified at the manufacturing stage (by specifying the 'in fill').

The question remains to what extent product / industrial designers must be knowledge-able on the inherent characteristics, materials properties and or process specifications of a particular AM process. We may assume that an industrial designer may require a general knowledge about AM capabilities because he or she may need to be knowledgeable about a wider range of potential processes and materials but also may not be directly involved in the series production. On the other hand, a design engineer employed in a manufacturing company may have become an expert in the materials and machine parameters of a spe-cific AM process. This in-depth knowledge is driven by dealing with the final stages of the design process, but also by being 'closer' to the actual manufacturing process (including the possibility to use it personally), as well as the fact that the company may have only a limited number of available technologies.

This is important because by clearly recognising the knowledge and expertise needed by the different types of designers, we can more confidently foresee future research direc-tions and develop more effective design education. Future research should focus on this area and provide an understanding of which knowledge designers need to be conscious of, knowledgeable in, and/or expert in.

Implications of DfAM for design studies

An interesting finding is that almost all studies distinguish between two types of DfAM guidance one type related to the *opportunities* of AM and the other to overcome inherent process *limitations*.

The first type includes highly abstract and general DfAM principles or heuristics that are called:

- AM design opportunities (Hague, Mansour, and Saleh 2003; Gibson, Rosen, and Stucker 2015; Thompson, Stolfi, and Mischkot 2016);
- AM design potentials (Hague, Campbell, and Dickens 2003; Kumke et al. 2017, 2016); or
- Opportunistic DfAM (Laverne et al. 2015).

These opportunities are often presented as qualitative descriptions or case studies and they express the unique capabilities provided by AM technologies. These opportunities seem to be fruitful at the conceptual design stage (Laverne et al. 2015, 2016) because they can facilitate the creative process and support the generation of innovative solutions that exploit AM distinctive capabilities. However, present DfAM studies have only partially stud-ied the inspirational impact of AM design opportunities on design (Doubrovski, Verlinden, and Horvath 2012; Maidin, Campbell, and Pei 2012; Kumke et al. 2017) and none have com-pared the impact of different media (e.g. visual vs textual) in conveying these opportunities. For instance, it has been demonstrated that the use of text as stimulus can have a pos-itive impact on creativity (Goldschmidt and Sever 2011). This may suggest that a textual description of design opportunities might be better suited for concept generation even if professional designers rely heavily on visual information (Gonçalves, Cardoso, and Badke-Schaub 2014) during idea generation (Casakin and Goldschmidt 2000; Goldschmidt and Smolkov 2006) because illustrative representations of existing examples may hinder idea generation (Jansson and Smith 1991; Purcell and Gero 1996; Perttula and Liikkanen 2006; Gonçalves, Cardoso, and Badke-Schaub 2014). Additionally, tangible three-dimensional

representations should be considered since they are highly valued and often utilised by professional designers (Gonçalves, Cardoso, and Badke-Schaub 2014) due to the amount and importance of information provided (Harrison, Earl, and Eckert 2015).

Clarify the context of validity

Commonly, AM is discussed as being a single manufacturing technology. Unfortunately, this may lead designers to assume that DfAM knowledge can be applied indiscriminately to any AM process. This assumption can be misleading since different AM technologies have fundamental differences requiring different design guidance. Additionally, most DfAM knowledge has emerged through experimentation using specific AM machines and materials and therefore this knowledge might only apply to a specific AM technology (e.g. FDM or SLS), a specific material or even a specific material-machine combination. Some researchers (e.g. Filippi and Cristofolini 2007; Adam and Zimmer 2015; Jee, Lu, and Witherell 2015) endeavoured to develop machine-independent design rules. However, although they all provided valuable frameworks to address this issue, they did not clearly distinguish between rules that are machine specific and those that are process specific. For instance, if a design rule states that the minimum wall thickness achievable for FDM is 2 mm, it should be made clear whether this is a limitation of the specific machine or if it is a limitation of FDM in general. Future studies should address this issue by either generating generalised design knowledge that can be successfully applied across different machines of the same process type or by explicitly declaring the context of validity of their findings.

A limitation of much current work that informs our framework is the lack of detailed evidence for validity of the guidance and rules within it. The aspect of validity becomes crucial when taking a deeper interpretation of design requirements for AM parts. The functional properties of AM parts depend upon varying factors such as material, build orientation, printing speed, accuracy, post-processing techniques, etc. some of which are not directly influenced by the form (shape) given by the designer and some that might be influenced or improved through changes in form. The achievement of specific design requirements may lead to conflicting outcomes. For instance, if a part requires mechanical strength in two or more perpendicular directions and the chosen AM process is anisotropic, the design requirements cannot be achieved by simply conceiving the part as with conventional manufacturing processes.

The contribution of all these possible factors on the achievement of design requirements is a challenge in the investigation of design guidance and rules and future research must take account of these parameters. Future studies need to explore the interconnection between design requirements and machine capabilities and the design strategies required to achieve the desidered outcomes. Consequenely, it becomes increasingly important that the context of validity is clearly stated in future research, especially where it contributes to the 'design rule' section of our framework.

Prominence of prescriptive studies

Another area of future work lies in the expansion of descriptive studies. Our review shows that so far, many studies on DfAM have been predominantly prescriptive, leaving questions about validity and applicability to industrial design practice largely open. As

Tomiyama et al. (2009) suggest, prescriptive design methodologies find fewer applications in industrial contexts because they are not aimed at concrete design goals. Moreover, systematic and structured frameworks are more likely to be adopted by large multinational companies, where common rigid procedures are needed to facilitate communication and ensure quality among large and spatially distant development teams. In contrast, structured frameworks can be viewed as superfluous in small companies where communications and common practices can be easily learned and shared among co-located colleagues.

Future studies should consider input from practitioners and investigate the adoption and utilisation of DfAM in practical settings. For instance, a topic of enquiry could be how practicing designers may adopt these approaches and how these approaches may influence professional design practice. Another approach could be to investigate the current understanding and application of DfAM in industry. Empirical evidence could greatly inform the development of DfAM knowledge and methods while fostering its adoption outside academia.

Emphasis on topology optimisation

In addition to part consolidation, lightweight design is another popular research area in AM. Lattice structures or structurally optimised geometries (i.e. topology optimisation) have received significant interest due to the ability to reduce weight and material usage and accordingly improve structural performance or energy efficiency (especially in aerospace). Indeed, the capabilities of AM processes have now provided a viable production outlet for the advances made in topology optimisation over the last 20–30 years.

By combing part consolidation and topology optimisation, Yang, Tang, and Zhao (2015) optimised a triple clamp design and the redesigned part was 80% of the weight of the original part. Schmelzle et al. (2016) reported a 60% weight reduction was achieved in redesigning a hydraulic manifold. However, whilst software to enable topology optimisation is becoming more prevalent, but is not yet a ubiquitous tool for designers.

Whilst topology optimisation has shown encouraging results in demanding engineering applications, for industrial design it may be less prominent. In fact, a strictly topology optimised geometry may neglect or even hinder other relevant requirements for industrial design applications (e.g. assembly, maintenance, cleaning, etc.). Indeed, designing to reduce complexity might be an important criteria for designers in order to ensure components are viable for volume production (Pradel et al. 2017; Pradel, Bibb, et al. 2018).

For the most complex components, generated through topology optimisation, AM might be the only viable production route. However, many components which have benefitted from topology optimisation might also be produced using more conventional processes (e.g. casting, maching). In addition, parts optimised for specific performance attributes (e.g. weight and strength) might not be optimal in other ways, such as production speed, machine utilisation or production cost.

Thus, whilst topology optimisation provides one route to DfAM, it is not the only route. Other design rules might be more appropriate for parts where high production volume is the main objective.

AM in generic material and process selection

Despite material and process selection for AM receiving attention since the late 1990s (Bibb et al. 1999), only a limited number of approaches have been proposed to support the selection process between conventional materials and processes and AM materials and processes. Different studies have highlighted how AM can be, in some circumstances, the most suitable manufacturing route (Atzeni et al. 2010; Sonova 2017). Therefore, easy-to-use and reliable tools for understanding when AM is a competitive alternative to conventional processes are urgently needed.

This review shows that existing methods suffer from limitations in providing this kind of support. Moreover, these studies have failed to equip designers with a reliable tool for selection at the early stages of the design process where data on the design is more qualitative but decisions carry the greatest impact (e.g. Ullman 2003).

Future studies should focus on developing selection tools with two major functions. The first will be to provide a catalogue of AM processes and their characteristics for rapid identification of the promising processes. The second will be to analyse a product or a component over a wide range of criteria (e.g. production volume and cost) and provide the appropriate process amongst AM and conventional processes. It is only after considerable experience that process selection becomes tacit knowledge, seamlessly informing the conceptual design stage and this remains extremely limited for AM and it is likely to remain so for many years. Therefore, decision support for designers is crucial in enabling AM. Another issue was the limited integration of AM material related knowledge in design and process selection tools. Our study could only partially address this topic. Given the breadth and depth, a dedicated study is required, and we will address this aspect in future studies.

Conclusions

In this paper, we have provided a framework for mapping current DfAM knowledge onto the typical design process. We have identified the limitations and future research directions for studies addressing DfAM.

The framework seeks to capture the main knowledge that has been developed to support industrial and product designers in designing end-use components for AM. This area is rapidly developing with new technologies emerging every year. Within this rapidly changing context, the framework provides a snapshot and a map for navigating the current state of the art. Whilst there are other reviews of DfAM (e.g. Rosen 2007; Yang and Zhao 2015; Thompson et al. 2016), this framework presents a comprehensive model targeted specifically at the product and industrial design practitioners, educators and researchers, assuming AM as a manufacturing process for the series production of end-use components. Building the framework has shown that several limitations affect existing DfAM knowledge and these have been described to provided suggestions for future research effort.

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Appendix 1

Summary of all literature

Where 'x' shows the research area that the authors focused on, and '(x)' indicates the area that the authors studied but not the focus of the research.

Author(s)	Year	Published in	Design process	Conceptual design	Embodiment design	Detail design	Process planning	Process selection	Primary validation method
3D Systems	2016	*White paper*				x			Not mentioned
Adam and Zimmer	2015	*Rapid Prototyping Journal*							Experiment
Adam and Zimmer	2014	*CIRP Journal of Manufacturing Science and Technology*							Experiment
Ameta et al.	2015	*Journal of Mechanical Design*				x	x		Review
Armillotta	2008	*Robotics and Computer-Integrated Manufacturing*						x	Case study
Atzeni et al.	2010	*Rapid Prototyping Journal*		(x)	x				Case study
Avnet and Elwany	2015	*Proceedings of the 2015 Industrial and Systems Engineering Research Conference*			x				Not mentioned
Ayre	2014	*White paper*			x	x			Not mentioned
Bibb et al.	1999	*Journal of Intelligent Manufacturing*						x	Case study
Boyard et al.	2014	*International Conference on Advanced Research in Virtual and Rapid Prototyping*	x	x	x	x			Case study
Byun and Lee	2005	*International Journal of Advanced Manufacturing Technology*						x	Case study
Comb	2010	*White paper*		x	x				Not mentioned
Conner et al.	2014	*Additive Manufacturing*						x	Case study
Doubrovski, Verlinden, and Geraedts	2011	*27th International Conference on Digital Printing Technologies*		x	x				Design experiment
Doubrovski, Verlinden, and Horvath	2012	*Solid Freeform Fabrication Symposium*		x					Survey
Eddy et al.	2015	*ASME 2015 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*						x	Case study
Elsbrock	2014	*ASPE 2014 Spring Topical Meeting: Dimensional Accuracy and Surface Finish in Additive Manufacturing*				(x)	x		Not mentioned
EOS GmbH	2014	*White paper*				x			Not mentioned

(*continued*).

Author(s)	Year	Published in	Design process	Conceptual design	Embodiment design	Detail design	Process planning	Process selection	Primary validation method
Fernandez-Vicente, Canyada, and Conejero	2015	*International Journal of Rapid Manufacturing*				x			Experiment
Filippi and Cristofolini	2007	*Research in Engineering Design*				x	x		Case study
Fornasini and Schmidt	2015	*20th International Conference on Engineering Design (ICED 15)*				x	x		Experiment
Gao et al.	2015	*Computer-Aided Design*		x	x				Review
Gibson, Rosen, and Stucker	2015	*Book*	x		x	x		x	Review
Gorguluarslan et al.	2015	*Journal of Mechanical Design*				(x)	x		Experiment
Govett et al.	2012	*Thesis*				x			Experiment
Hague, Campbell, and Dickens	2003	*Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*		x	x				Not mentioned
Hague, Mansour, and Saleh	2003	*Assembly Automation*		x	x				Case study
Hague, Mansour, and Saleh	2004	*International Journal of Production Research*			x	x			Case study
Hietikko	2014	*The International Journal of Engineering And Science*			x				Case study
ISO	2015	*Standard*	x		x			x	Standard
Jee, Lu, and Witherell	2015	*Solid Freeform Fabrication Symposium*				x	x		Case study
Jin, Li, and Gao	2013	*Robotics and Computer-Integrated Manufacturing*					x		Case study
Kannan	2013	*White paper*			x	x			Not mentioned
Kerbrat, Mognol, and Hasco	2015	*Robotics and Computer-Integrated Manufacturing*				x	x		Case study
Kim and Oh	2008	*Proceedings of the Institution of Mechanical Engineers – Part B – Engineering Manufacture*						x	Case study
Klahn, Leutenecker, and Meboldt	2014	*CIRP 25th Design Conference Innovative Product Creation Design*			x			x	Case study
Klahn, Leutenecker, and Meboldt	2015	*24th CIRP Design Conference Design*	x	x	x	x			Case study
Kranz, Herzog, and Emmelmann	2015	*Journal of Laser Applications*				x			Experiment
Kumke, Watschke, and Vietor	2016	*Virtual and Physical Prototyping*	x						Case study
Kumke et al.	2017	*International Journal on Interactive Design and Manufacturing*		x					Design experiment
Laverne and Segonds	2014	*CONFERE 2014 CROATIE*	x						Design experiment
Laverne et al.	2015	*Journal of Mechanical Design*	x	x					Design experiment

	Year	Source							Method
Laverne et al.	2016	*International Journal on Interactive Design and Manufacturing*		x					Design experiment
Leutenecker, Klahn, and Meboldt	2015	*International conference on engineering design*		x	x				Case study
Lindemann et al.	2015	*Rapid Prototyping Journal*						x	Case study
Maidin et al.	2012	*Assembly Automation*		x					Design experiment
Materialise	2016	*White paper*				x			Not mentioned
Munguía et al.	2010	*International Journal of Production Research*						x	Case study
Ponche et al.	2012	*Virtual and Physical Prototyping*			x	x			Case study
Ponche et al.	2014	*Robotics and Computer-Integrated Manufacturing*			x	x	x		Case study
Ranjan, Samant, and Anand	2015	*Proceedings of the ASME 2015 International Manufacturing Science and Engineering Conference (MSEC2015)*					x		Case study
RedEye	2014	*White paper*				(x)	x		Not mentioned
Rodrigue and Rivette	2010	*Proceedings of IDMME – Virtual Concept 2010*			x				Case study
Rosen	2014	*Virtual and Physical Prototyping*		x		x	x		Review
Rosen	2007	*Solid Freeform Fabrication Symposium*	x						Case study
Rosen	2014	*1st International Conference on Progress in Additive Manufacturing (Pro-AM 2014)*		x	(x)				Not mentioned
Salonitis	2016	*International Journal of Advanced Manufacturing Technology*			x				Case study
Salonitis and Zarban	2015	*CIRP 25th Design Conference Innovative Product Creation*		x					Case study
Samperi	2014	*Thesis*						x	Experiment
Schmelzle et al.	2015	*Journal of Mechanical Design*			x	(x)			Case study
Seepersad et al.	2012	*Solid Freeform Fabrication Symposium*				x			Experiment
Sells and Bowyer	2007	*White paper*				x			Not mentioned
Shelley	2013	*White paper*				x			Not mentioned
Smith and Rennie	2010	*Virtual and Physical Prototyping*						x	Not mentioned
Snyder et al.	2015	*Journal of Mechanical Design*				(x)	x		Experiment
Strano et al.	2013	*International Journal of Advanced Manufacturing Technology*				(x)	x		Case study
Stratasys Inc.	2015	*White paper*				x			Not mentioned
Teitelbaum, Schmidt, and Goaer	2009	*Proceedings of the ASME 2009 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*			(x)	(x)	x		Experiment

(*continued*).

Author(s)	Year	Published in	Design process	Conceptual design	Embodiment design	Detail design	Process planning	Process selection	Primary validation method
Thomas	2009	*Thesis*				x	x		Experiment
Thompson et al.	2016	*CIRP Annals – Manufacturing Technology*		x					Review
Ulu et al.	2015	*Journal of Mechanical Design*					x		Experiment
Urbanic and Hedrick	2015	*Computer-Aided Design and Applications*			x	x			Case study
Vayre, Vignat, and Villeneuve	2012	*45th CIRP Conference on Manufacturing Systems*			x				Case study
Vinodh, Nagaraj, and Girubha	2014	*Rapid Prototyping Journal*						x	Case study
Watts and Hague	2006	*Solid Freeform Fabrication Symposium*			x				Not mentioned
Whitney and Moultrie	2016	*14th International Design Conference, DESIGN 2016*					x		Experiment
Yang and Zhao	2015	*International Journal of Advanced Manufacturing Technology*	x						Not mentioned
Yang, Tang, and Zhao	2015	*Journal of Manufacturing Processes*			x				Case study
Zaragoza-Siqueiros and Medellín-Castillo	2014	*Proceedings of the ASME 2014 International Mechanical Engineering Congress and Exposition*				x	x		Case study
Zhang et al.	2014	24th CIRP Design Conference					x	(x)	Case study
Zhang, Xu, and Bernard	2014	*International Journal of Computer Integrated Manufacturing*						x	Case study
Zhou et al.	2014	*Proceedings of the 2014 International Conference on Innovative Design and Manufacturing (ICIDM)*		(x)	(x)		x	x	Not mentioned