DESIGNING END USE COMPONENTS FOR ADDITIVE MANUFACTURING

Navigating an emerging field

A REVIEW OF THE STATE OF THE ART

Contents

Executive Summary

Despite much excitement, research and development, Additive Manufacturing (AM) as a series production process for end-use components and products is not yet widespread or considered mainstream. However, there is a clear potential for AM to form a viable alternative to many conventional manufacturing processes, especially in low to medium production volumes.

A key enabler for this transformation is the capacity to design components and products that are both able to exploit AM capabilities and avoid its limitations.

In recent years, many studies have explored the topic of Design for Additive Manufacturing (DfAM).This report presents an overview of the state of the art of this research area. A systematic review has been carried out to identify the most significant academic studies on the topic. The review resulted in 66 key resources being identified and critically reviewed.

These resources have been reviewed and categorised using a generic model of the design process. This categorisation provides and easy and immediate way to map and navigate this emerging field.

Consequently, five major research areas are presented:

1. Process planning
2. Detail design
3. Embodiment design
4. Conceptual design
5. Design processes

In the discussion, these research areas are examined with the aim of highlighting shortcomings and providing future research directions.

Introduction

Additive Manufacturing (AM), also referred to as 3D printing, is leading towards a revolution in the way products are perceived. Unlike most conventional manufacturing techniques, AM forms objects by adding material in a layer-by-layer manner, rather than removing material from a larger mass or forming a set amount of material into a mould. AM enables complex geometries to be manufactured (Gao, et al., 2015). The key benefits of AM include design freedom, elimination of the need for tooling, reduced assembly, economic low volume production and product customisation (Ahuja, Karg, & Schmidt, 2015). Despite AM being widely heralded as *the next industrial revolution*, there are, in reality, still significant barriers to overcome for successful commercialisation (RAE, 2013; Wohlers, 2015). One of the most significant hurdles is the lack of design knowledge and practices targeted explicitly towards AM, which impedes the transition from *rapid prototyping* to the series production of mainstream, end-use parts using AM technologies (Adam & Zimmer, 2015).

For designers, engineers and AM practitioners to take full advantage of AM, a key requirement is understanding the processes and accordingly rethink the concept of design for manufacturing (DFM) (Ahuja, et al., 2015). The slogan 'if you can imagine it you can make it' has gradually been recognised as an idealistic statement. In fact, AM is far from 'skill free'. AM as applied to the production of final components is a relatively new idea and it is still developing, meaning that many designers will not yet have the tacit knowledge or experiences that allow them to apply AM potentialities and limitations to their concept generation. In recent years, many researchers have identified the insufficient availability of comprehensive design principles, rules and standardisation of best practices as one of

the major limiting factors in the uptake of AM (Meisel & Williams, 2015; Schmelzle, et al., 2015; Thomas, 2009). Therefore, **Design for Additive Manufacturing (DfAM)** research has drawn significant attention, which could result in a fundamental rethinking and redesign of products by considering AM capabilities.

A set of initial design principles and rules have been developed, which are summarised in the review papers by Gibson et al. (Gibson, Rosen & Stucker, 2010, 2015a), Yang and Zhao (Yang & Zhao, 2015) and Kumke et al. (Kumke et al., 2016). The majority of the works reported in these review papers can be divided into two groups, namely, qualitative design guidance and detail design rules. However, neither is able to provide efficient AM design methods for designers across the entire design process. For example, the design guidelines presented in Gibson et al. (Gibson et al., 2015a) are too general to be directly implemented. This does not provide tangible guidance to designers and will not radically influence the design process. Yang and Zhao (Yang & Zhao, 2015) reviewed a number of studies investigating threshold values of the geometrical parameters such as minimum printable wall thickness, minimum bore diameter and orientations. The design rules obtained from these studies only show the effectiveness in refining the shapes in the detail design stage to ensure the designed part can be successfully fabricated. These definitive rules are derived from a manufacturing engineering perspective that does not recognise industrial and product design practice. There is a lack of a new design framework that emerges as a result of the advances of AM technologies, which utilise AM advantages to facilitate the entire design process.

This paper first reviews the majority of the literature and then proposes a heuristic

framework, covering a broad view of design process, addressing the needs of industrial, product and engineering design contexts. This framework is aimed at equipping designers with an efficient design method and information in an appropriate format, consisting of different forms of guidance designers need during different stages of the design process. In addition, there is a growing need to investigate AM enabled design principles and methods. This need has been recognised in the academic community over recent years, particularly in 2014 and 2015, showing a dramatic increase in the number of attempts to understand and improve DfAM methods as depicted in

Figure 1.

This paper reviews the state-of-the-art DfAM design methods, frameworks and guidelines, covering the main stages of the design process including manufacturing process selection, concept generation, embodiment design, detail design and process planning. Section 2 provides an excerpt of the recent review publications on DfAM. Section 3 presents the robust literature review approach used in this study. This is followed by the brief introduction of a general design process model in section 4. Section 5 is the main section describing various AM-related design methods and guidelines. Section 6 comments on research in the literature and proposes a consolidated view of DfAM research areas, defining ambiguous terminologies including design rules, 3D printing process rules and part specification. Discussion and future trends in DfAM are presented in sections 6 and 7, respectively.
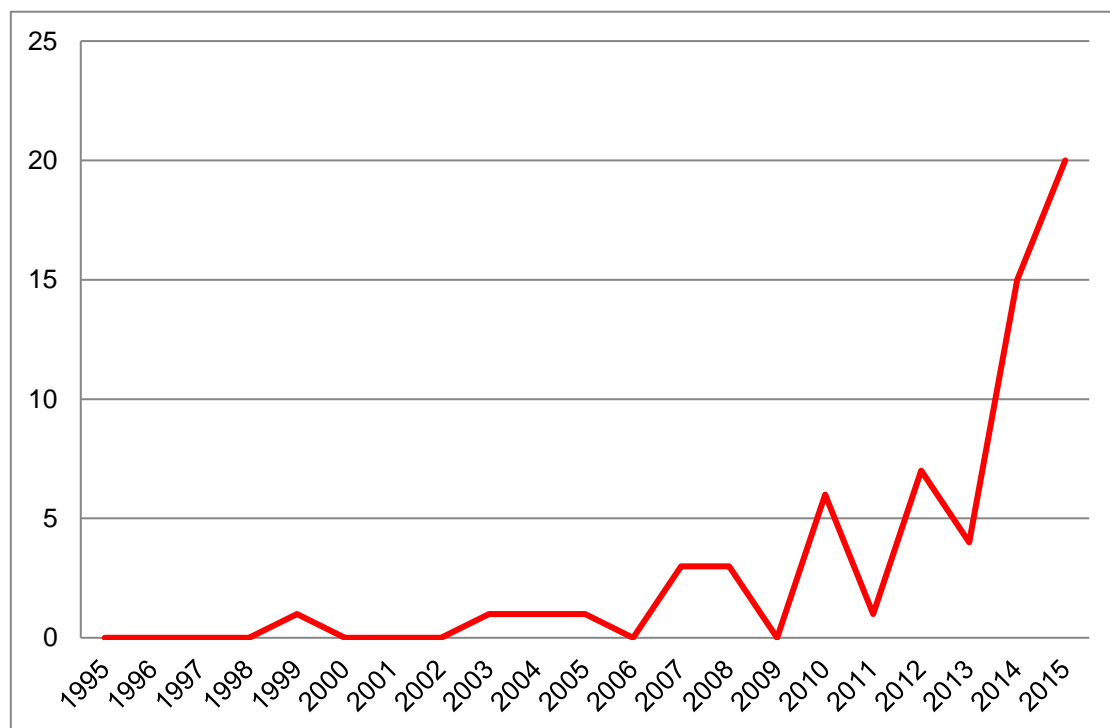

Figure 1: The number of publications from the year 1995 and 2015

Method

In order to identify all relevant studies on the topic of DfAM methodically, a systematic literature review (Kitchenham, 2007) was undertaken. The systematic review comprised distinct activities that involved:

1. The formulation of a review protocol

2. The collection of relevant documents

3. The review and exclusion of irrelevant studies

4. Analysis and synthesis of the remaining studies

During the formulation of the review protocol, relevant keywords were identified along with the inclusion and exclusion criteria, the search strategy, data organisation, analysis and synthesis. Keywords, inclusion and exclusion criteria were directly derived from the research questions and the aims described above. The general keywords "design for" and "additive manufacturing" were used in the automatic search with the aim of identifying as many relevant studies as possible (see Table 1).

Table 1: Summary of search queries

Database	Query
Scopus	TITLE-ABS-KEY("Design for Additive Manufacturing")
Science direct	("Design for Additive Manufacturing")
Web of science	TS=("Design for Additive Manufacturing")
Emerald Insight	"Design for Additive Manufacturing"
IEEE Xplore	"Design for Additive Manufacturing"
ProQuest	"Design for Additive Manufacturing"
Google scholar	"Design for Additive Manufacturing"
Google	"Design for Additive Manufacturing"

Research articles (from journals and conferences), white papers and blogs written in the English language and published from January 1995 to February 2016 were included in the study. Documents not directly related to the topic of DfAM and documents such as editorials, prefaces, poster sessions, panels and tutorial summaries were excluded. Further, when different versions of an article were found, only the most complete version was considered. Table 2 presents a summary of the inclusion and exclusion criteria adopted.

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Table 2: Summary of inclusion and exclusion criteria

Articles included	Articles excluded
Published between January 1995 to February 2016	Were not related to our research questions
Were written in English	Were outside our search time span
Were within the domain of design for additive manufacturing	Were of duplicated studies
	Were related to medical, biological, advance engineering or textile applications
	Were related to materials development
	Were related to technological development of the process
	Were related to economics of AM
	Were related to metal AM
	Were related to supports and infill design
	Were related to topology optimization
	Were related to tooling
	Were related to quality
	Were related to mechanical behaviour of AM parts

The search strategy consisted of seven stages as illustrated in Figure 2

Step 1. Automatic search:
Scopus (54 articles), Science direct (43 articles), ISI Web of science (80 articles), Emerald Insight (11 articles), IEEE Xplore (2 articles), ProQuest (68 articles), Google scholar (438) Google (38).

Step 2. Duplicated articles excluded (using EndNote):
194 references removed

Step 3. Articles excluded based on title & abstract:
368 References removed

Step 4. Articles excluded based on full-text:
30 references removed

Step 5. Snowballing:
45 references added

Step 6: Quality assessment criteria:
121 references removed

Step 7. Articles included in the review:
66 references

Figure 2: Summary of research strategy

Trends and demographics

This section provides the demographic results summarising the studies included in the literature. Here, the studies are presented with respect to their type of publication, temporal view, validation methods and relation with the design process

Type of publications

The majority of the studies included in the review were published in top journals and leading conferences that belong to the most cited publication sources in the AM domain. Thus, the top position of the publication source and their impact factor provides the confidence in the potential impact of this review and its overall quality. The distribution of studies derived from the publication channels is shown in **Error! Reference source not found.**. The majority of the studies are peer-reviewed journal articles (48%), followed by conference papers (34%). A few (6) studies where published from industry (9%) and the remaining (8%) comprised blogs, thesis, books and a project report.
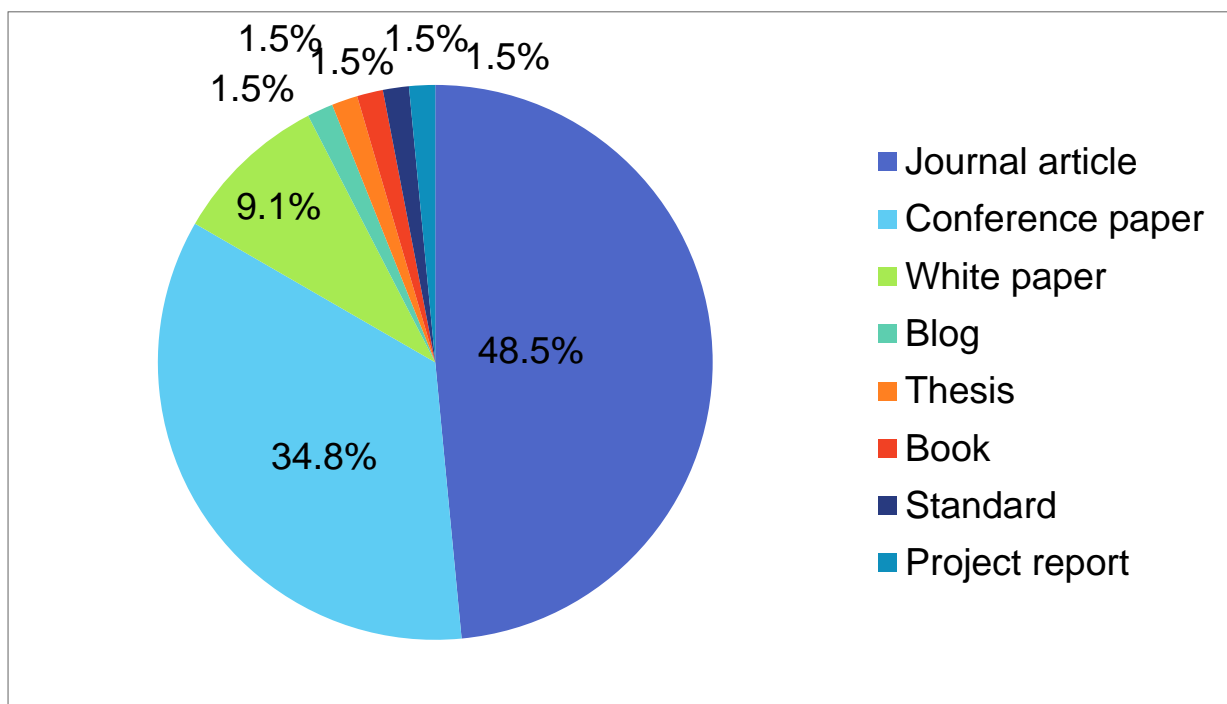
Figure 3: Primary studies distribution per publication source

Temporal view

The distribution of the primary studies throughout the years is presented in Figure 1. By looking at the year of publication, an increase in publication numbers can be noticed since 2009. Thus, it clearly demonstrates a rapidly growing interest in this area, which has been increasing exponentially from 2013 onwards. Figure 3 shows that the publication in the years 2012–2013 have increased by roughly 10 studies per year, while in the previous years from 1999 to

2007 little research was published (13 studies in total).

Validation methods

To classify the included studies, with reference to their research methods, a classification as shown in

Table 3 adapted from Glass, Vessey, & Ramesh (Glass, Vessey, and Ramesh 2002) was adopted. Figure shows the distribution of validation approaches. Out of the 66 studies, 35 reported case studies, 10 reported experiments, 3 studies reported design experiments, 1 study reported surveys and 3 studies reported a review method. On the other hand, 15 studies did not mention their methods used. It can be noticed that the validation methods adopted by the reviewed studies are dominated by case studies, followed by experiments and design experiments. The large number of case studies and the absence of more in-depth qualitative studies, such as interviews or ethnography, further support the idea that research to date has been mainly prescriptive and little attention has been given to current DfAM industrial practice.

Table 3: Description of validation approaches

Research method	Description
Case study	Studies included into this category validated the proposed design aid developing of one or more components or products.
Design experiment	Studies in which the design aid has been evaluated through a design activity carried out by other designers in a controlled environment.

Experiment	Studies using laboratory experiments and statistical analysis are included in this category.
Survey	Studies that fall into this category have used interviews or questionnaires to survey practices, opinions and so on from a (large) population.
Review	Studies that analysis the existing studies, typically with the aim of exploring the domain and understanding the concepts, fall into this category.
Not mentioned	Studies that do not mention any methods either implicitly or explicitly are sorted here.
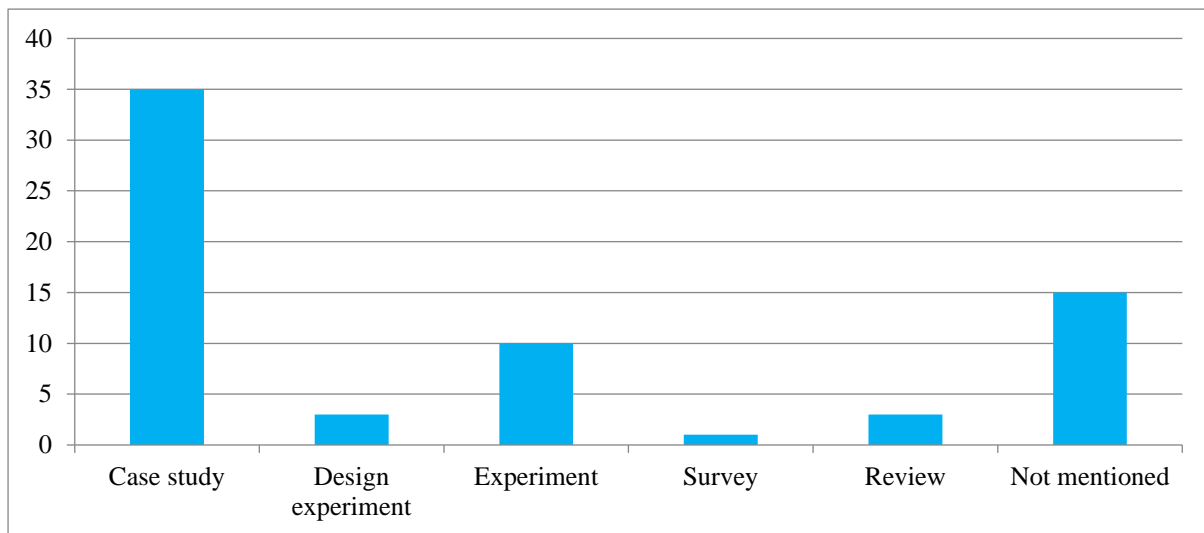
**Figure 4: Distribution of the validation approaches**
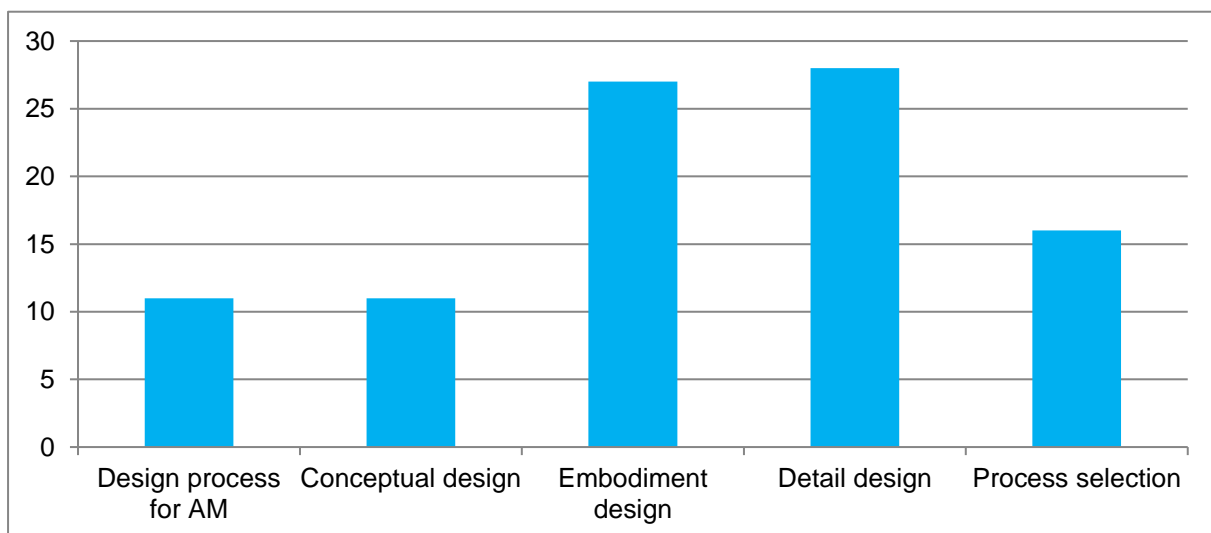
Figure 5: Distribution of DfAM methods at different stages of the design process

Finally, Figure 5 shows the distribution of DfAM aids at the different stages of the design process. As the literature suggests (Laverne et al. 2015) the graph shows that far little attention has been paid by the research community to the early stages of

the design process. Dissimilarly, far greater attention has focused on exploring design rules for ensuring manufacturability and part optimization.

DfAM in the design process
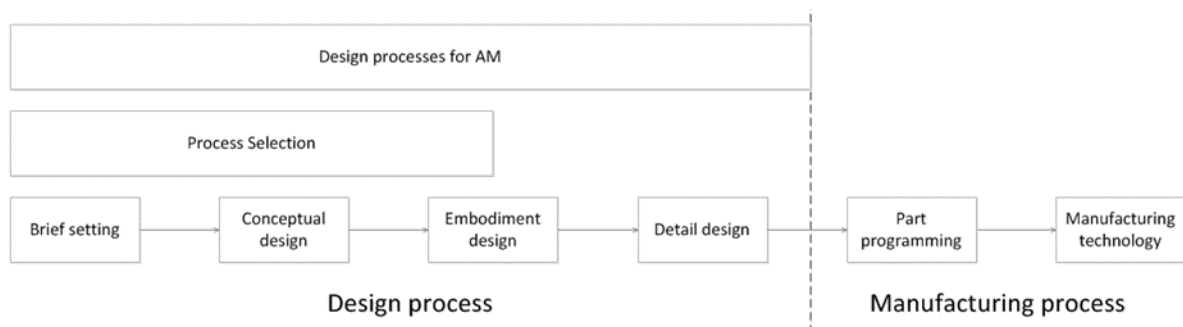
Figure 6: The design process model

Rosen (Rosen 2014) was the first to propose categorising DfAM studies using a design process model. Laverne et al. (Laverne and Segonds 2014) were the first to present an actual categorization although considering only nine studies. Kumke et al. (Kumke, Watschke, and Vietor 2016) expanded this classification including thirty studies, taking into account the opportunistic, restrictive or combined nature of the approaches and denoting partial or comprehensive coverage of the design process stage.

Our classification builds upon Kumke and Laverne's works by expanding the number of studies included and by adding additional categories. The four main phases of the design process as shown in

Figure 6, namely brief setting, conceptual design, embodiment design and detail design were considered. These design stages are consistent with several design process models (Trochim 2006; Smith and Eppinger 1997a; Smith and Eppinger 1997b; French 1985; Ashby 2011) being both descriptive and prescriptive (Cross 2008).

Moreover, three other categories were added. Design Processes for AM – a category that includes approaches targeted at the overall design process. Process Selection – a category that considers tools for identifying the most appropriate production process and Process Planning – a category that includes tools and methods for preparing parts for production. The process-planning category was included in order to categorise rules not pertaining to the design process itself. Differently from previous studies, a distinction was made between guidelines or rules that affect the geometry of the component and therefore relate to the design process and guidelines or rules that advise on how the production process should be performed. The studies reviewed are presented according to this classification.

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Terminology

The following technical terms are defined.

- **Design for Additive Manufacturing (DfAM)**. Unlike traditional design for manufacturing and assembly (DFMA) DfAM aims to take advantage of unique AM capabilities to

  (i) Design a new product in the beginning of the design process according to the functions of the product / component and the requirements of the selected AM process for production or

  (ii) Rethink, redesign and refine an existing design, utilising the characteristics of AM to improve the product / component functions. In the design process, AM is considered to be the technology for production. DfAM has typically meant that designers should tailor their designs to utilise the advantages of AM such as complex geometries and lightweight whilst considering the AM process limitations, to ensure the "printability" of the product.

- **Design rules**. Only those rules that are applied during the designing stages can be considered as design rules. A design rule should typically be

  (i) Applied from the beginning by the designer

  (ii) Applied to conceptual design and design development

  (iii) Directly within the control of the designer

  (iv) Applied through form giving (shape); and

  (v) Achieved through computer-aided design (CAD) software

For example, based on the above, the selection of in-fill pattern Fused Deposition Modelling is not recognised as a design rule because selecting different in-fill patterns does not affect the designed shape. Moreover, the designer does not directly decide the in-fill pattern to be used when designing the product.

- **3D Printing process rules**. Generally, a printing rule is employed to

  (i) Refine the designed structures in the detail design stage, usually referred to as engineering design

  (ii) Optimise geometrical features and

  (iii) Precisely define fillets, radii, wall thicknesses etc. by applying AM material/process specific parameters. In addition, printing rules should also be within the control of the designer, applied through form giving and achieved through CAD.

- **Specifications** (process guidelines). Specifications are information required for 3D printing processes, such as orientation and in-fill. Specifications can neither be expressed through form nor modelled in CAD but must be communicated to ensure that the printed features achieve the required accuracy, surface quality and strength.

Major research areas of DfAM

This section consists of six sub-sections, reviewing the major research areas on DfAM. The sub-sections are organised according to the general design process model presented in section 4.

Process planning

In general, process planning is the phase of the product development process in which a detailed plan for producing each component of the design is prepared. The main output is a process sheet for each component that specifies the sequential list of all the manufacturing operations required, along with the specific material utilised, the tooling and production machines needed and the estimation of the production cost (Scallan, 2003).

Process planning is associated with industrial or manufacturing engineering practice (Dieter & Schmidt, 2012). Since AM technologies are highly automated, the scope of AM process planning is usually narrow, which mainly consists of build orientation, support generation, slicing, toolpath planning, printing parameter optimisation (Jin, Li & Gao, 2013; Kulkarni, Marsan & Dutta, 2000). As shown in Figure 7, the AM process guidelines are applied to process planning for generating appropriate process parameters e.g. laser scanning strategy and support structures. This sub-section provides a brief review of AM process planning, highlighting the importance of process planning for DfAM.
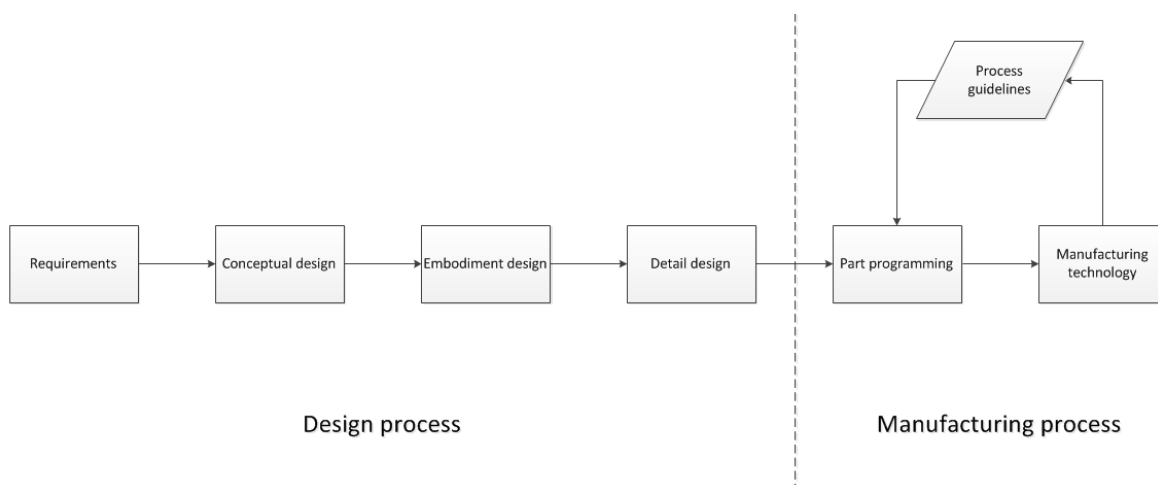
Figure 7: Process guidelines for AM process planning

Zhang et al. (2014) attempted to evaluate part designs and provide guidance for improvement from the AM process-planning point of view. Their proposed evaluation framework consists of four evaluation indicators that can be used to assess whether a given part is suitable for AM and which process is competent and cost effective for this specific part design. The indicators are defined according to

characteristics such as production cost, time, surface quality, orientation and build volume. For a given design, a unique threshold is first set by an experienced process-planning engineer. Subsequently, the indicators are employed to quantify the suitability of a part for AM production. If the evaluation result does not meet the threshold, suggestions will be given for modifying the design.

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Ponche et al. (2014) introduced the concept of global numerical manufacturing chain for the metal laser-cladding process, which starts with CAD, followed by a new DfAM methodology and finally NC program generation for production. The enabler for the numerical chain is the DfAM methodology consisting of three modules, part orientation, functional optimisation and laser-deposition toolpath optimisation. The majority of this research focused on toolpath optimisation, which optimises toolpaths in relation to the laser-cladding process characteristics and constraints based on the functional and mechanical requirements of the part.

Zhou et al. (2014) proposed a model that evaluates part geometries to determine whether a given part is feasible to be both technologically and economically manufactured by AM. The model correlates the mechanical properties (e.g. yield and tensile strengths, fatigue and hardness), part quality (e.g. surface roughness, dimensional accuracy and elongation) and production costs (e.g. energy consumption and build time) with process parameters (e.g. toolpaths and support structures). The AM process planning involves build orientation, support generation, CAD model slicing and toolpath planning. Design parameters are input into two modules, the process feasibility and planning module and the parameter optimisation module to determine the optimal process plan and process parameters in order to meet the design requirements including mechanical properties, accuracy and surface finish.

Kerbrat, Mognol and Hascoet (2011) propose a DFM methodology to estimate manufacturing complexity based on part features. Each feature is analysed and then the process (i.e. AM or machining) to be used to manufacture it is determined, in terms of manufacturing time, cost and feasibility of the processes. Manufacturing complexity was defined and divided into three categories, geometric parameters, material information (e.g. hardness, young modulus and thermal conductivity) and specifications (e.g. dimensional tolerance and surface finish) according to the attributes that affect manufacturing time, cost and quality; manufacturing process parameters; number of working operations required, respectively. Manufacturability indexes consisting of global and local indices were also defined, providing an elaborate view on which features would benefit from manufacturing by AM or machining. Starting with a CAD model, the manufacturability indices are calculated. The results suggest the areas of the part with easy-to-machine features that should be machined and the areas with difficult-to-machine features that can be additively manufactured.

The structural properties of AM parts are anisotropic and build direction dependent due to the layer-by-layer nature of the fabrication processes. Ulu et al. (2015) developed a surrogate-based optimisation algorithm capable of determining the build orientation that can maximise the mechanical strength of FDM parts under certain loading and boundary configurations. Snyder et al. (2015) studied the effects of build orientations on dimensional tolerance and surface roughness of SLM fabricated circular micro-channels. A test part comprised of 15 parallel micro-channels of 0.51mm in diameter and 25.4mm in length was built in three orientations i.e. horizontal, vertical and diagonal 45°. X-ray CT-scan non-destructive inspection was employed to measure the concentricity, circularity, total runout and surface roughness of the micro-channels. The measurement results indicate that the vertical direction produced the highest surface quality and the lowest concentricity, circularity and total runout. Elsbrock (2014) conducted a series of tests to study the factors that affect the success of the SLM process, including part orientation, shape of cross-section in relation to recoater blade collision, self-support structure for different materials and additional dimension allowance for secondary machining. Basic guidelines were provided to show how to modify a design from a stair-stepped surface requiring supports to a smooth curve without supports.

Strano et al. (2013) reported a study on an optimisation method that minimises the volume of support structure and generates graded cellular supports. The method was developed in the Matlab environment using .stl file as the input. The optimal part orientation that requires the minimum support volume is first identified. Subsequently, a pure mathematical 3D implicit algorithm is applied to generate cellular support structures. In the case study, the supports for a truss part were created, resulting in a reduction of 45% support volume as compared to solid cubic support.

Toolpath generation and optimisation have also been a focus of AM process planning research. Fornasini and Schmidt (2015) conducted an experimental investigation on the relationship between FDM deposition path and mechanical properties of printed parts. The results demonstrate the effects of in-fill densities, directions of the deposition paths and voids on the mechanical properties. The deposition path directions of 45-135° is suggested for obtaining the best plastic performance and the highest maximum tensile stress. A multilevel upscaling simulation model for characterising material properties of cellular structures of FDM parts was developed by Gorguluarslan et al. (2015). The inherent uncertainties in the FDM process are taken into account, including air gap errors, deposited material thickness errors, shrinkage errors and deviation of strut length. The uncertainties were quantified at the mesoscale level based on the experimental data, which were then applied to macroscale to predict the overall material properties of the target cellular structure with different orientations. Jin et al. (2013) developed an adaptive approach to improving CAD model slicing and toolpath generation for complex product models. In order to improve the geometrical accuracy while slicing the original CAD model, Non-Uniform Rational B-Spline (NURBS) curves were used to represent the boundary contours of the sliced layers. An adaptive toolpath generation algorithm was developed, which first generates toolpaths followed by

determining varying adaptive speed for the FDM deposition head to reduce build time.

As AM technologies are becoming mature and direct part production is more economically viable, the issues of geometric dimensioning and tolerancing (GD&T) associated with AM processes have arisen. Ameta et al. (2015) reviewed the implication of AM on current GD&T practices i.e. international specification standards including ASME Y14.5 and ISO 1101, and classified the issues into AM-driven specification issues and specification issues highlighted by AM capabilities. These issues were thoroughly discussed, including build direction and location, layer thickness, support structures, heterogeneous materials, scan/track directions, tolerancing freeform complex surfaces, topology-optimised features and functional features and internal features such as in-fills and lattices. A possible solution was proposed for each issue. For example, in order to specify the build direction of the part, the method in ASME 14.5-2009 can be adapted to identify a coordinate system using a notation with a unit vector to indicate the direction.

In summary, the research on AM process planning has focused on developing algorithms to optimise AM process parameters, support structures, build orientations, slicing strategies and toolpath generation. Some researchers such as Zhang et al. (2014), Jin et al. (2013) and Zhou et al. (2014) developed robust methods to systematically analyse two or more factors. This builds a bridge between process planning and the design process, providing suggestions for modifying the design from the process-planning point of view. Other researchers only studied one specific factor, for example, Strano et al. (2013) focused on support structure optimisation and Snyder et al. (2015) explored the effect of build orientation on part accuracy. Based on the above reviews, it can be identified that process planning directly determines whether the designed part can be successfully manufactured to achieve the desired part

quality. The integration of process planning in the design process is a promising method, such as the model developed by Zhang et al. (2014), which is able to evaluate the manufacturability of the part and provide suggestions on modifying relevant features.

Detail design

At the detail design stage, all the decisions regarding the product and its components are taken at the maximum level of detail so that every product aspect is fully defined. These decisions cover different design aspects such as arrangement, form, dimensions, tolerances, surface properties, materials and manufacturing processes (Ashby, 2011; Dieter & Schmidt, 2012; Pahl, 2007). Detailed analysis of functional, usable and financial performance at both component and product levels is carried out to evaluate every aspect of the design prior to moving to full-scale production

(Dieter & Schmidt, 2012). When all the final decisions are made and tested, the final design is communicated with detailed production specification in the form of engineering drawings and or CAD data (Ashby, 2011; Cross, 2008). This sub-section summarises the studies on developing detail design rules for different AM processes. As depicted in Figure 8 below, these rules are used to optimising and refining features at the detail design stage, according to the capabilities of AM technologies. The most representative research on DfAM detail design is by Adam and Zimmer (2015) and Kranz et al. (2015), where a set of detailed rules identifying feature types in relation to dimensions were obtained by taking AM capabilities into consideration. The aim of developing detail design rules is to ensure the success of the actual 3D printing processes and thus, the rules are primarily used to refine or optimise the features designed at the embodiment design stage.
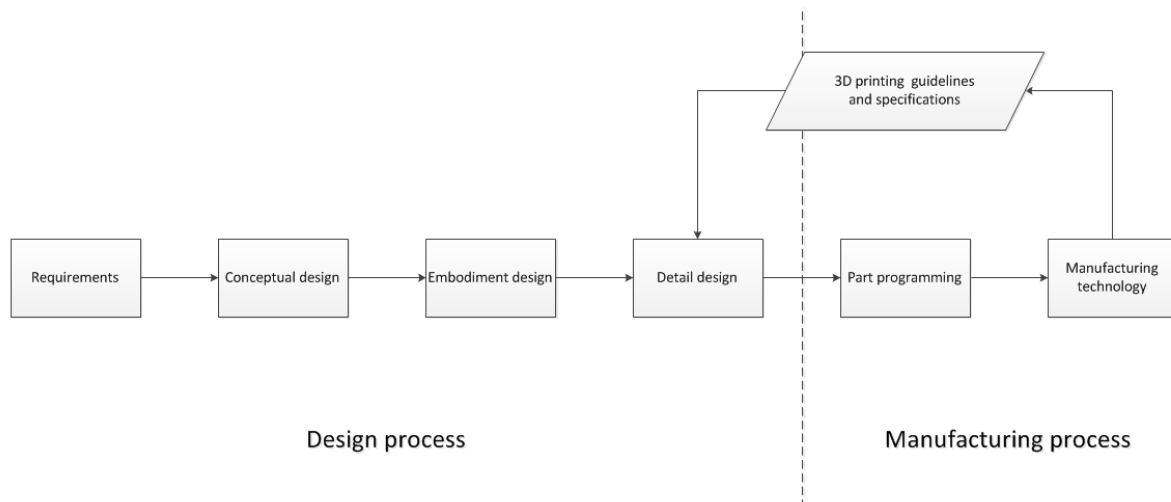
Figure 8: DfAM design rules for detail design

Adam and Zimmer (Adam & Zimmer, 2014, 2015) developed a geometry-based method, claimed as process and function independent that can be used to establish design rules for different AM processes. In this method, a part is treated as a number of standard elements including basic elements, element transitions and

aggregated structures. A series of tests were carried out to investigate the limits in printing these elements in terms of dimensional accuracy, surface quality and material accumulation. Typical features that consist of these elements include wall thickness, outer and inner edges, gap height, width and length and overhang length. The thresholds were obtained

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when the print tests failed, indicating that the AM process had reached the limit of the printing capability. A comprehensive set of rules have been developed, identifying the key factors that affect SLS, SLM and FDM manufacture of walls, cylinders and bores and thus providing guidelines in feature optimisation.

Kranz et al. (2015) conducted experimental investigations on part accuracy and surface quality of SLM thin walls, bars and bores in relation to part orientation, position and size. Extensive guidelines were derived, taking into consideration, part accuracy, surface quality, manufacturability, production time and post-processing capability (i.e. machining). The guidelines cover a wide range of prismatic features including cavity, feature integration, wall, bore, gap, beam, hollow cylinder, ellipse, overhang and support.

Urbanic and Hedrick (2016) investigated design rules for building large and complex components in FDM. The functional approach was employed to identify the minimum wall thickness, self-supporting overhangs and appropriate orientations. The guidelines also suggest not building springs with more than 5% voids as it significantly reduces the mechanical strength. Fernandez-Vicente et al. (2015) applied an experimental approach using geometrical test specimens in order to establish design limitations for FDM. The results include indications on how overhang length and thickness affect accuracy, how layer thickness affects quality, how angles influence quality and how bridge length increases deformation.

Meisel and Williams (2015) investigated Polyjet manufacturing constraints that influence part designs, which were support material removal, minimum resolvable (manufacturable) feature size, feature survivability during cleaning and minimum self-supporting angle. These constraints are imposed by the Polyjet machine attributes as well as the processing method and materials used. A series of

experiments were conducted to analyse how the constraints were affected by the Polyjet process parameters. A preliminary set of design guidelines containing minimum recommended parameter thresholds were established.

Seepersad et al. (2012) designed a series of benchmark parts with different features and varying dimensions and clearances, which aimed to investigate limiting feature sizes for different types of feature in order to establish a designer's guide for dimensioning and tolerancing SLS parts. The designed features include circular holes, slits, lettering, thin walls, gears and shafts. SLS printing was implemented to determine the feature and font resolutions and the clearances for mating gears. The results indicate that the minimum hole diameter is 0.6 mm in the horizontal direction, walls should be greater than 0.8 mm, the recommended clearance for a shaft is 1 mm and separation of a gear tooth is 0.5 to 1.0 mm. Govett et al. (2012) further extended this work, investigating SLS design rules. The rules were obtained through exploring the capability of a specific 3D Systems' SLS machine in fabricating the finest negative features (i.e. holes and gaps), and the thin wall features (i.e. wall thickness, pin diameter, distance from a hole to a wall and font size) in relation to build orientation and plate thickness. The suggested tolerances for these features were also provided.

Thomas (2009) evaluated the capability of the SLM process and developed a set of feature-based detail design rules in relation to geometrical limitations and material properties, including typical SLM features and process parameters such as overhangs, supports, convex and concave radii, surface roughness as a function of orientation, tapping and reaming self-supporting holes, shrinkage and stock-on material. Other similar studies include Teitelbaum, Schmidt and Goaer (2009), who developed FDM design guidelines for optimising heights, form ratios, overhangs, holes and orientations. Zaragoza and Medellin (2014) developed three sets of design rules for FDM, which are design for

geometry, design for quality and design for sustainability. In design for geometry, the authors identified the rules for support structures, cavities, overhangs, etc. In design for quality, distortion, shrinkage, surface finish, process stability and post-processing were discussed. In design for sustainability, production cost and environmental considerations were addressed.

Using AM to create a joint mechanism in one printing operation is likely to result in the fusion of the two joint components if the gap between them is too small. This is also partially due to the capability of the specific AM process and machine used. In order to use the same AM machine whilst achieving a smaller joint clearance thus enhancing the stability of movement, Song and Chen (2012) proposed an add-on marker structure. For a cylindrical pin joint mechanism, portions of the internal journal were expanded into a number of markers and accordingly, the related external bearing shrinks into dents. By doing so, the overlapping regions between the journal and the bearing were largely reduced, which avoids the fusion and thus ensures the rotation between the journal and the bearing.

Filippi and Cristofolini (2007) developed a universal knowledge-based system, entitled design guidelines (DGLs), based on the ISO-GPS (geometrical product specification) concept. The DGLs aim to enable designers to modify and optimise products to ensure compatibility with different manufacturing and verification technologies. The DGLs consist of five connecting levels, namely compatibility, rules, design, manufacturing and verification domain floors. The considerations in manufacturing and verification are integrated in the design rules. Each level, as indicated by their names, evaluates the relevant aspects of a design and suggests necessary changes.

Apart from academic research, industries have developed more comprehensive and robust detail design rules covering a vast number of features. For example,

Materialise NV (2016) developed rules for designing 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) provided extensive FDM detail design rules including, in addition to the above mentioned features, shrinkage, warping, pins, threads, undercut fillets, draft angles, living hinges, text, finishing and secondary operations. 3D Systems, Inc. (2015) and EOS GmbH (2014) also published similar design rules and considerations for SLS. Ayre (2014), Crucible Design Ltd., presented a list of design rules for SLS and FDM. In contrast to Hague et al. (2004), Ayre (2014) suggested maintaining thin and uniform wall thicknesses.

In general, detail design rules can be summarised as follows:

(i)   They are highly process dependent. For example, SLM detail design rules cannot be directly applied to other AM processes. Having said that, the rules for one specific process might be used as a good reference for other similar processes but the thresholds would need to be investigated.

(ii) They were typically obtained by conducting a large number of experiments. Hence, the typical features and thresholds might not be transferable from one AM process to another.

(iii) They are descriptive and communicated by a set of features together with dimensions. They are routed by the capability of the specific AM process, machine and material.

They generally are not publically available. Industry developed rules, including academic research projects funded by industrial partners (e.g. the DMRC projects at the University of Paderborn, Germany), have developed

comprehensive detail design rules for certain AM processes such as SLM, SLS

Embodiment design

In embodiment design, the promising design ideas generated in the concept design stage are further developed (2012). During this stage the design ideas are defined and structured at a greater level of detail (Cross, 2008; Pahl, 2007). The overall layout of the design is defined and the considerations relating to size, shape, strength, materials, spatial compatibility and cost are addressed (Dieter & Schmidt, 2012). The output of embodiment design

and FDM but have not made them publicly or freely available to a wider audience.

is usually a general arrangement drawing or a CAD assembly that will be used to evaluate the design and check it against financial and performance criteria, usually in the form of a Product Design Specification or PDS (Pahl, 2007). After this stage, every major change to the design will become increasingly expensive and difficult to make. This sub-section includes studies that provide guidelines and tools for (re)designing features/products by taking advantage of AM whilst and ensuring the manufacturability by AM, as shown in Figure 9 below.
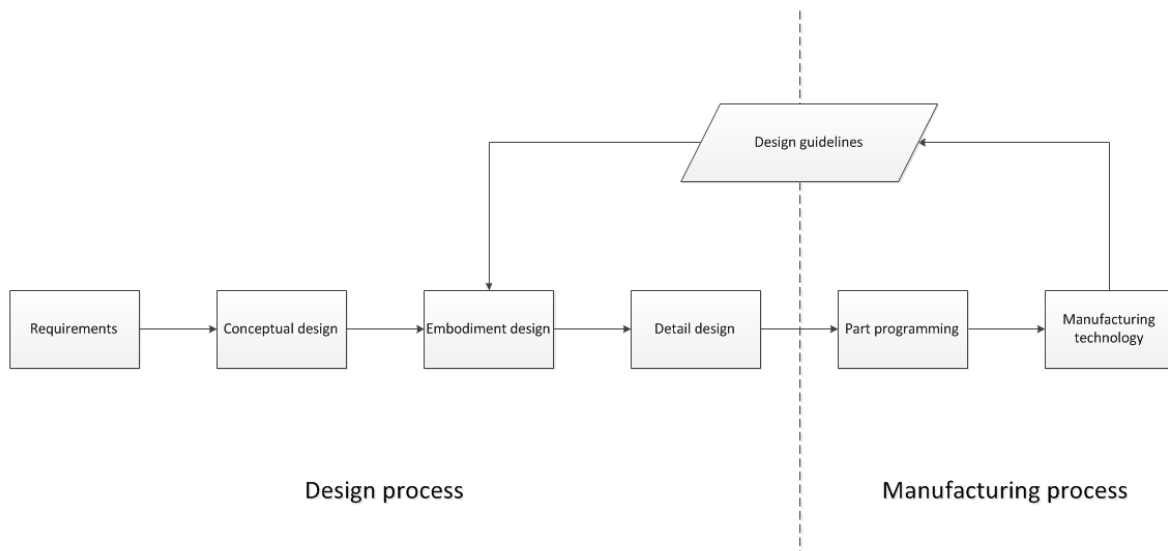

Figure 9: DfAM guidelines for embodiment design

In the very early stage of DfAM research, researchers were of conflicting opinions on the advantages as well as the constraints that AM could bring to design practice. Some researchers were cautious and suggested sticking to conventional design methods (Richard Hague, Campbell & Dickens, 2003). Hague, Campbell and Dickens (2003) pointed out two concerns for designers. Traditionally, a product consists of a large number of assembled components. When designing a new product for AM, the designer is

suggested to incorporate the existing proven design to accommodate these components. However, this may introduce new constraints into the new design. In addition, designers still need to consider design for assembly and maintenance principles for some products such as electrical circuit boards. On the contrary, some DfAM pioneers advocated the use of AM as it released almost all design constraints. Hague, Mansour and Saleh (2004) compared DFM and DFA rules for injection moulding with AM technologies

and stated that any complex shapes designed in a virtual environment can be directly translated into a physical product. This also has an impact on assembly because it is possible to reduce part count. This design philosophy was then tested on two case studies, where a diesel fuel injection system and an electronic enclosure were redesigned and then manufactured by SLS, to demonstrate the advantages of AM in part consolidation, complex shape design and production cost.

Watts and Hague (2006) conducted a preliminary investigation on a genetic algorithm based on topology optimisation. Heterogeneous part structures that exhibit a uniform stress distribution were created by varying the densities of single elemental cells and volume fractions. A preliminary DfAM methodology for cellular structure generation was proposed, focusing on (i) reducing the mass; (ii) minimising maximum displacement, thus increasing stiffness; and (iii) minimising the difference between the maximum and minimum Von Mises stress values. Rodrigue and Rivette (2010) proposed an embodiment design method, combining an algorithm with a numerical method for part consolidation. Avnet and Elwany (2015) adopted a design structure matrix to model architecture of complex products and subassembly. The capability of the 3D Systems ProX 100 metal production machine was integrated in the model. A multi-level design method has been developed by Zhou et al. (2014) for reducing the number of components whilst improving product performance. The method starts with the primitive geometry analysis that complies with the design constraints and functionality, followed by an optimisation algorithm to remove redundant material.

Ranjan et al. (2015) developed a feature graph based design method, which addresses the relationship between part structures and direct metal laser sintering (DMLS) process parameters. A producibility index was proposed, capable of quantitatively evaluating the manufacturability of a designed part in the selected build orientation. The main parameters in the index include sharp corners, small holes, thin regions, cusps, support structures and surface area contacting support. The design method iteratively evaluates the original and modified designs until the producibility index indicates that there is no feature that may lead to the DMLS production difficulty.

An ISO standard (ISO, 2015) identifies six AM design potentials that can be further explored to improve embodiment design, namely, lightweight, internal structures, functional integration, surface structures, customised geometries and materials. The design considerations are also defined, including material usage, sustainability, business, material properties, process and communication. Product considerations contain part consolidation, features for ease of assembly, multi-part mechanisms, compliant mechanisms and process chains.

The majority of the DfAM research on embodiment design has focused on developing redesign methods, utilising the geometrical design freedom provided by AM to significantly improve the functionality of the product and reduce part count. Klahn, Leutenecker and Meboldt (2014) introduced a substitution method to redesign conventionally designed products for AM production. The main redesign guidelines include integrated design for part consolidation, individualisation for more variations and smaller batch sizes, lightweight design for reduction of production time and costs and design for efficiency improvement. The DfAM methodology developed by Ponche et al. (2012) has three major steps. The first step is the geometric analysis, which determines whether the part dimensions are compatible based on the dimensional characteristics of the specific AM process. The second step is to determine the functional volumes, which are the features/surfaces that have significant effect on the product performance. Having confirmed the functional surfaces can be manufactured, the linking volumes that

connect the functional surfaces are created based on XY, YZ and XZ planes. Yang, Tang and Zhao (2015) also proposed a similar redesign method, aimed at reducing part count and weight through part consolidation and topological optimisation. The original design is first analysed, identifying the functional surfaces that determine the performance of the final product. These surfaces are kept unchanged in the design process and then, the structure linking them is created. Finally, the structure is optimised by filling with homogenous lattices and skins to reduce the part volume.

Atzeni et al. (2010) presented some general DfAM rules such as rethinking assembly towards integrated freedom design, reducing part count and using as little raw material as possible. These rules were then applied to the redesign of a fluorescent lamp holder. Two cost estimation models were developed for estimating production costs for injection moulding and SLS, respectively, by taking into consideration, machine, labour and material costs. The production costs for varying volumes were compared, indicating that SLS is economically viable for medium batches and mass customisation of up to 87,000 pieces.

Vayre, Vignat and Villeneuve (2012) presented a general AM design method. The expected part functions and specifications are first analysed to identify the important functional features/surfaces. An initial shape is then generated, addressing the functional features that are not allowed to be modified in the later stages. Then manufacturing constraints of the selected AM process and topological optimisation is applied, ensuring the remaining features are manufacturable and their volumes are minimised. Finally, the optimised shape is validated by either virtual manufacturing or real prototyping. However, it should be noted that each of these steps requires a great deal of computation and the validity of this design method needs to be further assessed.

Schmelzle et al. (2015) redesigned a hydraulic manifold, which originally consisted of 17 pieces, into a single part, realising 60% and 53% reductions in weight and height, respectively. The finite element analysis (FEA) technique was employed to analyse the stress distribution in the internal passage geometries, providing guidance to merge components. The manifold was designed to be made of hollow structures to reduce weight and save production time. Additional features were also added to ensure the success of the SLM process and the following finish machining processes. A generalised redesign approach for part consolidation was proposed, addressing the key requirements for both metal AM and post-processing. The approach can be summarised as follows: (i) defining system boundary, (ii) specifying internal and external geometry using FEA, computational fluid dynamics (CFD) and topology optimisation when appropriate, (iii) specifying the build orientation to minimise build time and material usage while considering distortion and surface quality, (iv) specifying build supports and (v) identifying post-processing needs such as the need for support removal, fixtures and assembly.

Based on the above description, it can be identified that redesign has been proven to be an effective way to exploit AM capabilities to improve product performance in the embodiment design stage. In general, the aim of redesign is to optimise the structure through reducing part count. Redesign can be summarised in three major steps as follows:

(i) identify functional surfaces that largely determine the product performance, which should not be modified;

(ii) construct the linking features that connect the isolated functional surfaces;

(iii) employ topology optimisation to reduce material volume.

However, it should be noted that redesign methods are only applicable to optimising existing product designs that were originally conceived using conventional design methods targeting traditional manufacturing process such as injection moulding and machining. Redesign methods will need to be further developed to address the customer requirements and the design ideas from the 'requirement' and 'conceptual design' stages shown in Figure 9. On the other hand, there has been debate whether to use AM in the embodiment design stage. Klahn et al. (2015) and Leutenecker et al. (2015) compared two manufacturing strategies i.e. functional driven and manufacturing driven strategies for low volume production. The functional driven strategy applies DfAM design practice, following the requirement of the selected AM process in the beginning of a product design and development whilst ignoring all conventional design rules. By contrast, the manufacturing driven strategy requires designers to comply with established conventional design rules. The benefit of this approach is that once a product is established in the market and subsequently requires an increase in production volume, it can be easily transferred to a high volume mass production process. Klahn et al. (2015) and Leutenecker et al. (2015) found that there were only minor differences between AM and conventional versions of a design. However, the improvements in product performance enabled by the functional driven design strategy were not discussed.

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 (Cross 2008; Smith and Eppinger 1997b; Ashby 2011). This sub-section includes studies that provide tools or methodologies for supporting AM at the conceptual design stage as shown in Figure 10 below.
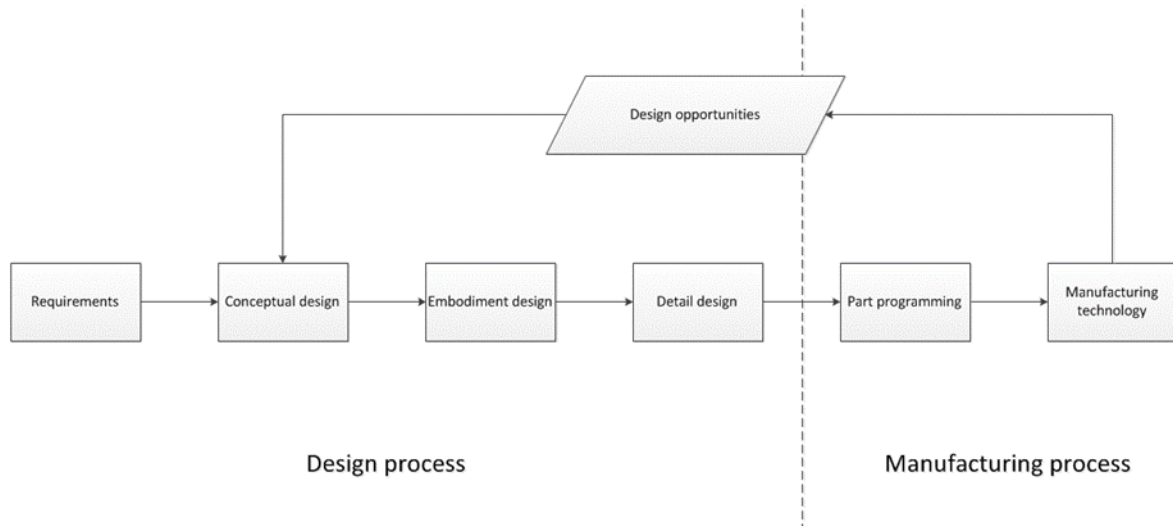
Figure 10: DfAM opportunities for conceptual design

It was only until recently that DfAM for conceptual design attracted the attention of the academic research community. The first attempt to provide a tool for DfAM at the conceptual design stage was made by Rosen in 2007 (Rosen 2007). Rosen recommended a biomimetic approach called 'reverse engineering biological systems' aimed at retrieving from nature design solutions that could be exploited via AM. The approach was based on four phases: biological systems identification,

biological representation, biological strategy extraction and strategy abstraction. Validation was carried out through the development of a morphing aircraft wing. Despite the innovative contribution, the approach was only briefly exposed with no attempt to assess effectiveness and consider implementation and implications in product design theory and practice.

Maidin, Campbell and Pei (Maidin, Campbell, and Pei 2012) were amongst the first to propose a method for supporting DfAM at the early stages of the design process. A database containing design features was used to provide designers with a set of design solutions suitable for AM. The idea was to convey AM potentialities by presenting a number of appropriate design solutions categorized in four design principles. Maidin's taxonomy of design features covered user fit (customization to accommodate the user), improve functionality, consolidation and aesthetic. The application of the database was evaluated with two design experiments and a survey. Two groups of participants made of eight design students and seven design professionals were used. The results suggested that the database was very beneficial for design students, while it was less meaningful for professional designers. The paper then suggested the development of an online database. Whilst the study offered a pioneering investigation on DfAM aids for conceptual design, it made no attempt to investigate the impact of different techniques in conveying AM knowledge. Moreover, the findings would have been more relevant if the researchers had achieved a larger sample size in the experiments. The effectiveness of the database with professional designers with no or little experience in AM was not investigated. Built on the work of Maidin, Campbell and Pei (Maidin, Campbell, and Pei 2012), Doubrovsky (Doubrovski, Verlinden, and Horvath 2012) proposed a wiki, an online sharing platform, for the collection and distribution of design experiences and examples of AM applications among product designers. The wiki was developed in a design education context and evaluated through usage analysis and questionnaires. The survey showed how a wiki could be perceived as a valid method for informing users on AM capabilities if the quantity of information available is sufficiently generous. Doubrovsky's innovative study corroborated Maidin's findings and especially corroborated the positive effect of a database of solutions with design students. However, the absence of validation with professional designers limited the scope of the study. Likewise, Laverne, Segonds, Anwer and Le Coq (Laverne et al. 2015) studied the effects of AM knowledge on concept generation adopting a database approach. Using design experiments with three groups of participants (novice, novice with AM examples and AM experts) the study analysed the concepts generated by the groups after being exposed to AM knowledge. The concepts were analysed for quantity of ideas generated, originality and manufacturability. The study suggested three impacts of AM knowledge on concept generation. AM knowledge appeared to indirectly affect the quantity of concepts and concept originality, while concept manufacturability did not increase with AM knowledge. Based on these findings, a design process of four stages was suggested. The study offered an insightful analysis of DfAM at the conceptual design stage. However, the small sample size and a limited analysis of the material provided to convey AM knowledge during the experiments reduced the impact of the study.

Laverne, Segonds, D'Antonio & Le Coq (Laverne et al. 2016) proposed a tailored AM knowledge (AMK) for enhancing the adoption of AM in the early stage of the design process and fostering the achievement of innovative solutions. The study performed three experiments targeting three aims, defining which type of AMK designers need at the conceptual design stage, which kind of media they preferred and during which stage and divergent or convergent activities. The first experiment showed that designers tend

not to use AM when dealing with projects that require certification; AMK can be useful when dealing with direct manufacturing especially opportunistic AM rules; designers also stated that AMK is more useful in increasing functionality. The second experiment showed that text seems to be appreciated by ergonomists but not as much by engineers and designers, while artefacts, video and images seem to be appreciated by all of them. Experiment three seems to suggest that "complexity for free" is considered valuable in divergent activities but less so in converging. Machine attributes were considered valuable when dealing with converging activities. The paper presents several different contributions to the research on AMK in the early stages of the design process; however, there are some flaws in the methodology. For instance the approach adopted cannot be considered an experiment in the strict sense, but instead a survey and interview research. In the first experiment, the sample of participants is relatively small. The binary scale provides a rough indication of usefulness and the connection with Gibson's AM capabilities remains unclear. In the second experiment is not clear what "expert skills" refers to and the removal of artefact is quite arbitrary.

Differently, Boyard, Rivette, Christmann and Richir (Boyard et al. 2014) proposed a modelling approach for supporting the design of AM parts in relation to functional requirements. The approach consisted of a graph diagram representing functions and constraints of a given product architecture. The graph facilitated the design of complex part's geometries at the early stages of the design process. Additionally, it prevented late and costly design modifications by abstracting manufacturing constraints and satisfying both design for assembly (DfA) and design for manufacture (DfM). At the stage of development presented in the paper, the approach suffered from the lack of validity since evaluation with professional designers and implementation in an industrial context were not carried out or shown to be effective.

Numerous studies have attempted to support DfAM providing summaries of AM design opportunities (Comb 2010; Hague et al. 2003; Gibson, Rosen, and Stucker 2010). Given their generic and abstract nature, these summaries are included in this stage and considered as inspirational material for idea generation. The following papers borrowed from academia and industry illustrates this category of studies. In the very early stage of DfAM research, Hague et al. (Hague et al. 2003) compared the design potentialities of AM with those of injection moulding. The authors reported five potentials of AM on design such as the production of complex components without cost increment, the removal of any geometrical limitation given by the process, the use of multi-materials, the customization of parts and customer-driven design. Hague's seminal study was of great significance as it marked the first attempt to define AM opportunities on design; however, the paper made no attempt to explore the implementation of those opportunities in design practice. Similarly, Comb (Comb 2010) proposed in a white paper a design methodology based on four design guidelines namely 'forget design for manufacturability', 'focus on function', 'iterate', 'refine the design' and 'question tradition'; and five design techniques such as 'make it feature rich', 'rethink wall thickness', 'consolidate or segment', 'fill the envelop' and 'ignore the details'. The paper offered a valuable insight on DfAM principles, even if it lacked any concrete examples. In fact, one of the main drawbacks of proposing AM opportunities is the generic and abstract nature of the guidelines that make them difficult to be understood and adopted especially by less experienced designers. This can also be associated with the modes in which those guidelines are presented. Very often they are conveyed only with a short title, a brief text explanation and an example. This may not be sufficient to provide a comprehension of the principle and to foster its application into practical cases.

Recently Salonitis (Salonitis 2016) adopted the axiomatic design method for

assessing the manufacturability of design ideas. Customer requirements, functional requirements, design parameters and process variables were considered with a zigzag decomposition through three domains. AM guidelines were derived both from the literature and a survey that involved thirty-five UK AM bureaux. A case study was used to describe and validate the method. The findings supported the effectiveness of axiomatic design theory in evaluating design alternatives at the early stages of the design process. Salonitis' paper provided a systematic and structured procedure for considering AM potentialities and constraints in concept selection. Nevertheless, the highly prescriptive and systematic nature of the procedure, may limit its applicability to more creative industrial design.

Collectively, these studies support the notion that DfAM for conceptual design has not been widely or rigorously investigated. Neither the quantity nor the quality of the studies provides a clear picture of the methods and tools that should be used to support industrial designers at the conceptual design stage. Regarding the quality, the main flaw of the presented papers lies in validation. Very few studies have made an attempt to corroborate their approach with professional designers. Moreover, when this has been done, other flaws were present such as a limited sample size, a lack of comparison with different approaches or lacking consideration of pre-existing literature on concept generation. Another important aspect is the exclusively prescriptive nature of the proposed methods. Up to now, far too little attention has been paid to investigating current practices of AM experts when designing products and components.

Design processes for AM

The interest in a comprehensive design process for AM is relatively recent (Kumke, Watschke, and Vietor 2016; Yang and Zhao 2015); however, in the early stages of DfAM research, Rosen was the first to propose a design process for AM based on Pahl and Beitz's design process model (Rosen 2007). As shown in Figure 11, Rosen's process provided a comprehensive overview of DfAM considering conceptual design, manufacturing process selection, later design development stages, process planning and manufacturing simulations. Nevertheless, the approach suffered from some limitations. For instance, no attempt was made to validate the process with designers and the focus was still on the later stages of the design process. In fact only one method (biomimicry) was proposed for the conceptual design stage while several were suggested for the later stages. Finally, the approach did not consider objectives more familiar to industrial design such as user requirements, ergonomics and aesthetics.The section summarises the studies that proposed an overall design process for DfAM. These processes usually considered all stages of the design process, from the brief setting to the final product
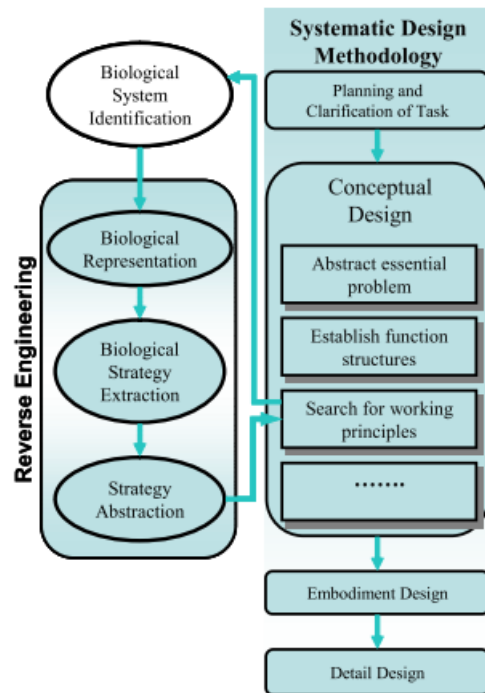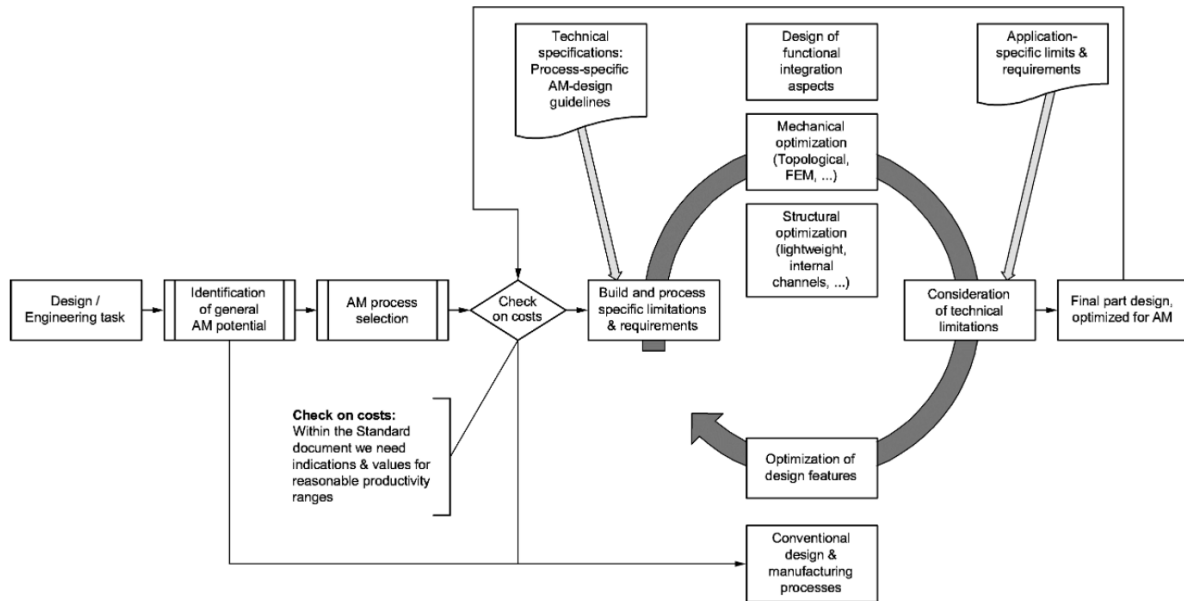

**Figure 11: Rosen's (2007) DfAM process**

Figure 12: ISO's (2015) overall strategy for product design

In a recent paper, the International Standard Organization ISO (ISO/ASTM 2015) proposed an overall AM strategy for product design. The strategy was based on a development cycle initiated with design/engineering task clarification, followed by identification of general AM potentials and AM process selection, which defined whether AM was a suitable manufacturing route. Consequently, process specific limitations were identified followed by an optimization stage in which the functional integration and structural optimization were performed. Finally, considerations of technical limitations and final part design completed the process.

Differently, Yang and Zhao (Yang and Zhao 2015) proposed a two-stages design methodology for AM shown in Figure 13. In the first step of the methodology, an analysis of the initial CAD data was performed with potential part consolidation driven by functional and performance requirements. In the successive step, different optimization methods were applied to the newly generated design space in order to achieve higher performances. If no design solution was

achieved, the process iterated the function integration with necessary modifications. The process provided an innovative approach to DfA and DfM for AM considering part integration, structural optimization and manufacturability; however other design requirements, for instance ergonomics or aesthetics were neglected. Moreover the need for a CAD file relegated the approach to later stages of the design process.
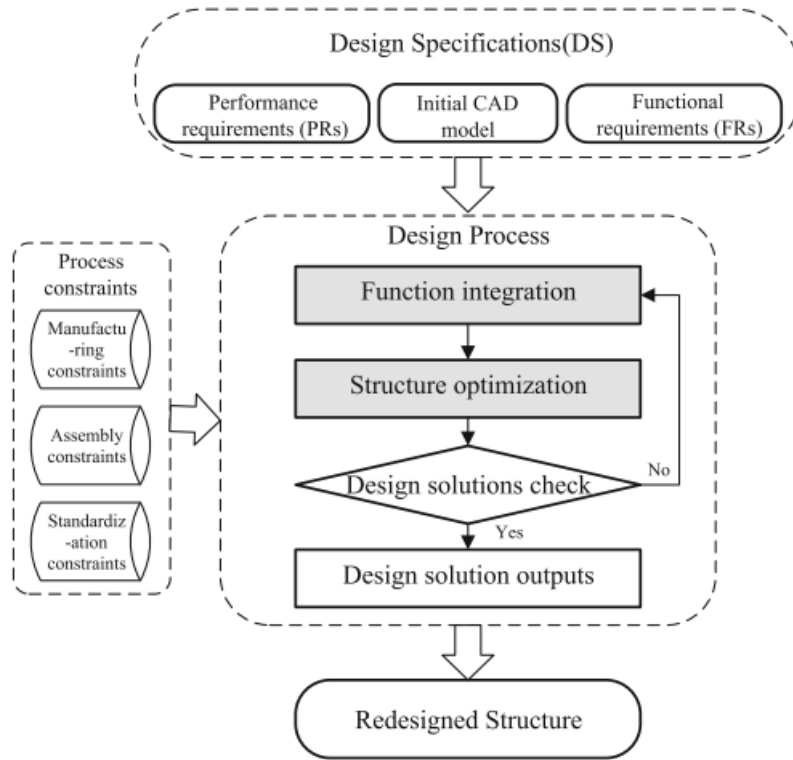
Figure 13: The AM-enabled design method proposed by Yang and Zhao (2015)

In 2015, Klahn, Leutenecker & Meboldt (Klahn, Leutenecker, and Meboldt 2015) described two potential design strategies for AM in product development. The first design strategy called "manufacturing-driven" assumed that AM would be the temporary manufacturing process for the initial series production of a product or component, when high production volumes are not yet required. Once the product achieves adequate volumes, AM would be substituted with a conventional mass production process. Therefore, designers had to comply from the beginning with the design rules of conventional processes and not consider AM capabilities. In contrast, the second design strategy called "function-driven" assumed that AM would be the final manufacturing process. Therefore, designers were supposed to focus on the functionality of the product ignoring the limitations of conventional processes. As shown by the cases, the principles provided by the authors were very interesting for product design practice; however, their abstract nature implied that subsequent work should have been carried out to apply these strategies in real case scenarios. Moreover, a more systematic approach to validate and describe the strategies would have increased the relevance of the study.
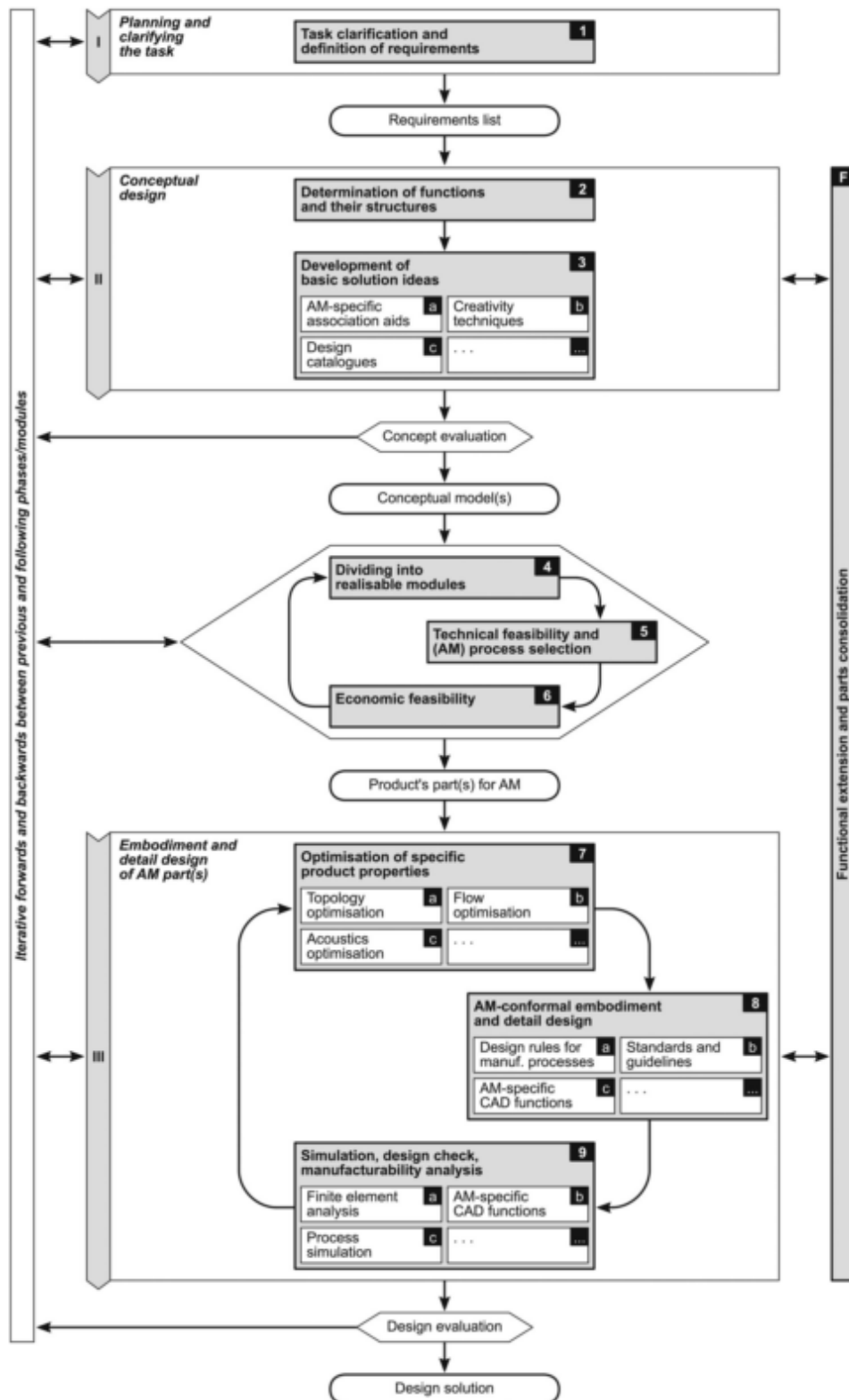
Figure 14: Kumke et al.'s (2016) DfAM framework

In order to integrate different existing DfAM tools and methods and provide and an overall framework for DfAM, Kumke et al. (Kumke et al., 2016) proposed a design process based on the general VDI 2221 process model and its four stages, namely planning and clarifying the task, conceptual design, embodiment design and detail design. The model offered a detailed, structured and comprehensive approach to DfAM integrating previous methods and tools at the different stages of the design process. However, given the prescriptive and systematic nature of the framework, the approach was centred on engineering design and mechanical engineering rather than industrial / product design. Another major drawback was the lack of validation, which narrowed the scope of the study.

A general lack of validation and the exclusively prescriptive nature of the proposed design processes are the two most important themes that emerge from the studies discussed so far. Validation remains, if present, a mere description of a limited number of cases. Little attention has been given to investigating how professional designers may adopt these approaches in their professional practice. This limitation reduces the validity of the studies and raises concerns about their generalisability and applicability to design practice. Another similar issue lies in the 'almost' exclusively prescriptive nature of the design processes. As Tomiyama highlighted: "*Design methodologies are widely taught but they find less industrial applications*" (Tomiyama et al. 2009). This seems to suggest that more attention should be given to understand current design practice in AM and which specific approaches, if there are, are used for designing AM product or components. Empirical evidence may greatly inform the development and applicability of DfAM design processes.

Discussion

The present study was designed to provide a framework for the methods and tools so far developed for addressing the issue of designing products or components for series production with AM. As this research shows, an increasing number of studies have been published in the last two years, suggesting an expanding interest for this topic and a very dynamic rapidly-evolving context. The framework provides at the same time a snapshot of the current state of art and a conceptual tool for organizing this knowledge. The following section describes the overall framework proposed in this report, followed by a descriptive statistical analysis of the reviewed studies and a discussion of the design methods and tools organised by design process stage.

Design for Additive Manufacturing framework

The framework presented in Figure 15 describes the communication of additive manufacturing knowledge in the design process. The framework integrates the four conventional design process stages namely brief setting, conceptual design, embodiment design and detail design and two stages of the manufacturing process, the manufacturing technology itself and the process planning. The knowledge of the manufacturing technology is transferred from the domain of the production process to the design process as shown by the arrows. The knowledge feeds different stages of the design process and can assume different form according to its relevance for a specific design stage. For instance, during embodiment design when designers define the product layout, the methods for part consolidation are meaningful because they relate to that specific activity. Moreover, the same kind of knowledge can take different form and level of detail

in relation to the stage of the design process that is targeted. An example is given by the rule *"in order to reduce time and cost use the lowest possible building height"*. This rule can be conveyed as a design opportunity at the conceptual design stage and therefore inspire product designers to conceive as flat as possible design ideas. However, it can be conveyed as a design guideline in the embodiment stage and therefore guide industrial designers in designing as flat as product layout or components. Or, it can be conveyed as a design rule in the detail design stage, where it supports design engineers in developing the geometrical features of the components. Finally, it can also be conveyed to the process planning stage where it will inform process engineers on how to orient the part on the building platform.
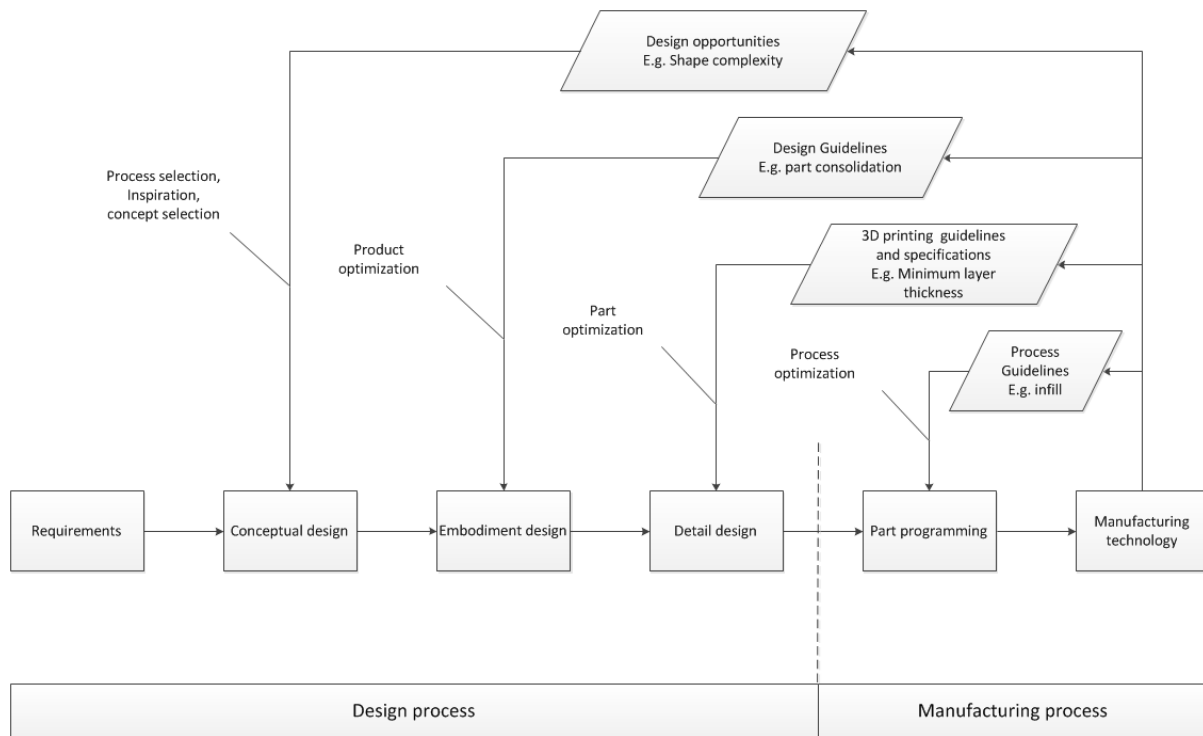
Figure 15: The DfAM Framework

DfAM Terminology

As identified in the literature review, there is no consensus on the terminology regarding DfAM methodologies, methods and tools. An interesting finding is that almost all studies (Kumke, Watschke, and Vietor 2016; Yang and Zhao 2015; Laverne et al. 2015; Hague et al. 2003; Gibson, Rosen, and Stucker 2010) distinguish between two different types of design rules. The first type relate to particular AM capabilities and are qualitative in nature (Yang and Zhao 2015). These are also called *potential of rapid manufacturing on design* (Hague et al. 2003), *design guidelines* (Yang and Zhao 2015), *unique AM capabilities* (Gibson, Rosen, and Stucker 2010), *AM design potentials* (Kumke, Watschke, and Vietor 2016) and *opportunistic DFMA*

(Laverne et al. 2015). The second type are more quantitative in nature and similar to traditional DfM rules (Boothroyd and Dewhurst 2008; Poli 2001; Bralla 1998). These focus on ensuring manufacturability by communicating the limits and constrains of AM and are referred by the academic community as *design rules* (Yang and Zhao 2015), *AM design rules* (Kumke et al., 2016), *restrictive DfAM* (Laverne et al. 2015) and *design constrains* (Hague et al. 2003). This finding suggests the diverse nature of DfAM aids and supports our framework and classification. Moreover, future studies should explore the connection between these two types of DfAM rules and their applicability of the design process. Tentatively, design guidelines should be more appropriate for the early stage of the design process in which the design is not yet defined and more creative approaches can be adopted to

generate innovative solutions that exploit AM capabilities. While more quantitative guidelines should be used later on to ensure manufacturability, improve quality and reduce production cost.

Process planning

The research on AM process planning includes developing algorithms to optimise AM process parameters, support structures, build orientations, slicing strategies and toolpaths generation. Build orientation and toolpath generation related to in-fill patterns are the dominant research areas. It has been well known that using different orientation and in-fill patterns can lead to different dimensional accuracy, surface quality and mechanical properties of the printed object. Researchers have made significant effort on finding the optimal build orientation and in-fill pattern for various part geometries for achieving the desired properties. The integration of process planning in the design process is a promising method, such as the model developed by Zhang et al. (2014), which is able to evaluate the manufacturability of the part and provide suggestions on refining relevant features based on AM process capability. It has demonstrated that, despite the part being designed according to AM design practice, proper process planning still plays an important role in ensuring the part to be manufactured achieves the design requirements.

Detail design

The majority of the DfAM methods, particularly detail design rules, are communicated by feature types and dimensions. In general, detail design rules are descriptive and provided in the form of manuals, where a number of features are classified into groups such as walls, cylinders and overhangs and the suggested thresholds e.g. minimum printable wall thickness and hole diameter are given (Adam & Zimmer, 2015). The

thresholds were obtained by conducting a vast number of 3D printing tests. Furthermore, in comparison to academic research, industry (e.g. 3D Systems Inc. and Stratasys Ltd.) as well as international standards e.g. ISO have developed more comprehensive detail rules for optimising designed features covering most of the typical features in engineering design, for example, chains, hinges, threads and snap clips. Whilst detail design rules on SLM, SLS and FDM have been thoroughly studied, they are typically not publically or freely available.

Moreover, it is noted that, although the thresholds are only valid for the specific AM systems as the AM capabilities may vary depending on different AM systems (manufacturers) and materials, the developed rules provide valuable guidance for design practice. Some researchers such as Adam and Zimmer (2015) and Filippi and Cristofolini (2007) endeavoured to develop process-independent design rules. Adam and Zimmer (2015) proposed a systematic approach to investigating detail design rules for different AM processes. The framework by Filippi and Cristofolini (2007) basically contains a massive database where the attributes of different manufacturing processes e.g. machining, casting and AM are included. Therefore, strictly speaking, neither of studies by Adam and Zimmer (2015) and Filippi and Cristofolini (2007) has provided process-independent detail design rules. In addition to developing process-independent detail design rules, Jee et al. (2015) propose a process-independent expression method to present and formalise design rules as a set of modular components and formalisms. A typical expression is written in the 'IF and THEN' format i.e. Category (type), if *[conditions]* then *[consequences]*, where 'category' is the feature type (e.g. overhang), and 'type' is the type of consideration (e.g. circular, hole and angular). An example of 'condition' is 'designed at greater than around 45 degrees of undercut angle and built by FDM'. Then the 'consequence' is 'self-supporting'. This modular expression

method is able to present design rules for different AM processes in a universal manner.

Since detail design rules have been well researched, new thinking should focus on how to utilise the rules to further optimise the design rather than simply changing the feature dimensions according to the capability of the AM process/machine. A typical example is the add-on marker structure used in a joint mechanism proposed by Song and Chen (2012). This structure utilises the capability of the selected SLA machine in terms of the minimum printable feature size to fabricate joint journals and bearings.

Embodiment design

In the embodiment design aspect, the vast majority of embodiment design research has focused on developing part redesign methods, which take an existing part design by a conventional design method and modify certain features specifically for AM production (Schmelzle, et al., 2015). The motivation behind redesign is primarily concerned with part consolidation, reducing part count and thus the difficulty and cost of assembly. Despite part consolidation improving certain features of a part, it is not able to guide designers to conceive a completely new product based on customer requirements and basic design concepts. Ponche et al. (2012) provided a new embodiment design method, which first identifies functional surfaces, followed by creating features/volumes linking the functional surfaces whilst considering material usage.

In addition to part consolidation, lightweight design is another popular research area. Lattice structures or structurally optimised geometries by topology optimisation are receiving significant interest due to the ability to reduce weight and material usage and possibly reduce production time. By combing part consolidation and topology optimisation, Yang et al. (2015) optimised a triple clamp design and the redesigned

part was 80% of the weight of the original part. Schmelzle (2015) reported a 60% weight reduction was achieved in redesigning a hydraulic manifold. Whilst topology optimisation has shown the superiority in certain application areas, it should be pointed out that industrial design does not necessarily rely on lattice or other similar topologically optimised structures. Topology optimisation neglects the simplicity of daily products and thus misses the simpler opportunities for industrial designers.

In contrast to embracing AM technologies, Vaughan and Crawford (2013) debated that existing conventional design methodologies along with virtual models can still be used to design AM parts with complex material properties and designers do not have to revamp their design methods due to the introduction of AM technologies. A case study of two fastener mechanism designs were presented, in which the fasteners were designed using a conventional design method and then fabricated by SLS. Although the statement by Vaughan and Crawford (2013) holds true, mostly because of the enhanced capabilities AM provides, the traditional design methods do not address the AM characteristics, thus are unable to utilise the unique advantages of AM to improve design efficiency. Additionally, Klahn et al. (2015) and Leutenecker et al. (2015) are of the opinion that it may not be necessary to consider AM characteristics in the early stage of the design process. They demonstrated two distinct manufacturing strategies i.e. functional driven and manufacturing driven strategies for low volume production. The functional driven strategy applies DfAM design practice, whereas the manufacturing driven strategy requires designers to comply with established conventional design rules. It was found that only minor differences between the AM and the conventional version of a design existed. In this case, the manufacturing driven strategy shows the advantage in facilitating the scaling up from low volume AM production to mass production by using a conventional manufacturing process.

Conceptual design

Experienced designers typically embark on concept generation and conceptual design based on their tacit knowledge and previous experiences (Weisberg 1999; Pasman 2003; Eckert, Stacey, and Earl 2005; Oxman and Oxman 1992; Keller et al. 2009). Since AM as applied for the production of final components is still recent and developing, many designers may not have the tacit knowledge or experiences that allow them to apply AM potentialities and limitations to their concept generation. Commercial industrial design is frequently a very time and cost constrained activity (Chevalier and Ivory 2003) that cannot always accommodate protracted reference to technical resources or trial and error experimentation or experiential learning, especially during the concept design stage (Liikkanen et al. 2009). It was only recently that DfAM for conceptual design attracted the attention of the academic community (Rosen 2007). Overall this review has found only seven studies that explicitly propose tools and methods for the conceptual design stage. Among these seven studies, four proposed a database of design solutions for communicating AM capabilities (Maidin, Campbell, and Pei 2012; Laverne et al. 2015; Doubrovski, Verlinden, and Horvath 2012; Laverne et al. 2016), one study (Rosen 2007) proposed a structured approach for retrieving design ideas for AM, another (Boyard et al. 2014) suggested a modelling technique for representing functions and one study (Salonitis 2016) proposed a structured method for concept selection. The database approach, which aims at fostering the understanding of AM capabilities and their application in design, has been the most studied. This method has been validated through design experiments and surveys with design practitioners and students. Although these validations are more informative than case studies, the studies suffer from a low number of participants and some flaws in the analysis. For instance, Laverne et al. (Laverne et al. 2015) fails to give sufficient consideration to the material used in the study to convey AM knowledge to the participants. Therefore, it remains difficult to understand the relationship between the learning material adopted (for instance, the cases presented in the database) and the findings. This also makes it difficult to relate these results, for instance to the use of visual material (Laverne et al. 2016) with previous studies on inspirational sources and their effect on the design process. In fact, it has been widely demonstrated that designers rely on visual information (Hanington 2003; Burris and Henderson 2001; Muller 1989; Sarkar and Chakrabarti 2008), independently of their level of expertise (Gonçalves, Cardoso, and Badke-Schaub 2014) and especially during idea generation (Casakin and Goldschmidt 2000; Goldschmidt and Smolkov 2006), different drawbacks have likewise been highlighted. Various studies have shown that idea generation can be hindered by the use of illustrative representations of existing examples (Jansson and Smith 1991; Purcell and Gero 1996; Perttula and Liikkanen 2006). Moreover, it has been proven under experimental conditions, that using text as stimuli has a positive impact during idea generation (Goldschmidt and Sever 2011). Additionally, Gonçalves, Cardoso, & Badke-Schaub (Gonçalves, Cardoso, and Badke-Schaub 2014) highlighted that an over-reliance on visual stimuli may have a fixation effect and that three-dimensional representations are highly valued and often utilised by professional designers, potentially due to the amount and importance of information provided (Harrison, Earl, and Eckert 2015). So far none of the reviewed studies have considered these results in DfAM for conceptual design. Future studies should explore more in-depth different content and formats for conveying AM capabilities and study their impact among design practitioners.

Design process for AM

The studies on design process clearly indicate that there is ongoing research

investigating comprehensive design methodologies for AM (Yang and Zhao 2015; Kumke, Watschke and Vietor 2016). Currently some important limitations still affect the proposed design methodologies, the most important being validation. According to the reviewed literature few frameworks have been validated at the time of writing (Boyard et al. 2014; Kumke, Watschke, and Vietor 2016; Yang and Zhao 2015; ISO/ASTM 2015) while others are under validation at the moment (Laverne et al. 2015). The only study presenting a validation (Klahn, Leutenecker, and Meboldt 2015), adopts a case study approach. Another limitation lies in the prescriptive nature of these methodologies. As Tomiyama (Tomiyama et al. 2009) suggests, prescriptive design methodologies find fewer applications in industrial contexts because they are not aimed at concrete design goals. Moreover, a systematic and structured framework is more likely to be adopted in a large multinational company, where common rigid procedures are needed in order to facilitate communication and ensure quality among large and spatially distant development teams. Contrarily, structured frameworks can be experienced as superfluous in an SME where communications and common practices can be easily learned and shared among a small, co-located team. Future studies should consider more rigorous validation methodologies including input from practitioners and investigate the adoption of DfAM into a variety of large and small design teams.

Process selection

Regarding process selection methods and tools, while several methods have been developed for comparing and selecting the most suitable AM process, very few methods have been proposed to support the selection of the best alternative between conventional and AM processes. Different studies (Atzeni et al. 2010) and companies highlight how AM can be, in some circumstances, the most suitable manufacturing route. The creation of easy-to-use and reliable tools for understanding when AM is a competitive alternative to conventional processes are extremely needed. Our review shows that existing studies suffer from some limitations in providing that sort of support. We identified two kinds of studies. The first kind provides some generic guidelines stating under which condition a part should be considered for AM. Conner's reference system (Conner et al. 2014) provides a clear and understandable map of AM applicability. The system seems to be suitable for the very early stages of the design process since it requires very little information from the design; however, the system does not consider one important limitation in AM which is part size. Klahn et al. (2015) provided a quick and easy list of selection criteria to identify when a part is suitable for being redesigned for AM. The criteria provided only qualitative and generic indications and they did not consider key economic and quality variables such as production volumes, materials, accuracy and size. The *Trade-off Matrix* proposed by Lindemann seems to be an interesting tool for evaluating when a part would be effectively produced by AM. However, the approach seems to be intended for dealing only with parts that have already been fully developed and produced. Considering the information required for the evaluation, which includes also processing time for conventional processes, it seems that the matrix is not applicable for concepts or design ideas. Zhou et al. (2014)'s system for evaluating process feasibility for part geometry considering design parameters as well as process capabilities provides a suitable tool for assessing whether an AM process is capable of producing a defined part. Since the system requires CAD data, it is suitable only for later stages of the design process. Although Zhou's approach provided insightful suggestions for finding alternatives to conventional machining processes, the system failed to compare the advantages and disadvantages of the different AM processes. Future studies that will focus on developing process selection tools have to look into two directions. The first will be to provide a

catalogue of AM processes and their characteristics (Swift and Booker 2003; Ashby 2011) for rapid identification of promising processes. The second will be the development of tools that are able to analyse a product or a component over a wide range of criteria and indicate which process AM or conventional are the most suitable for its production (Swift and Booker 2003).

Conclusions

This report has explored the key literature on Design for Additive Manufacturing (DfAM). This literature has been organized using a design process model to help the reader to organise and navigate the available body of knowledge on this topic.

This report can be used to understand the current state of the art of DfAM knowledge and facilitate the retrieve of DfAM knowledge for specific applications.

We strongly encourage design practitioners to make use of this report and engage in providing insights on new areas of development and future research directions. The report provides them with a snapshot of the current knowledge on the topic from the perspective of industrial and product design practice.

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