Design for additive manufacturing – a review of available design methods and software

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Abstract

Purpose – This paper aims to review recent research in design for additive manufacturing (DfAM), including additive manufacturing (AM) terminology, trends, methods, classification of DfAM methods and software. The focus is on the design engineer's role in the DfAM process and includes which design methods and tools exist to aid the design process. This includes methods, guidelines and software to achieve design optimization and in further steps to increase the level of design automation for metal AM techniques. The research has a special interest in structural optimization and the coupling between topology optimization and AM.

Design/methodology/approach – The method used in the review consists of six rounds in which literature was sequentially collected, sorted and removed. Full presentation of the method used could be found in the paper.

Findings – Existing DfAM research has been divided into three main groups – component, part and process design – and based on the review of existing DfAM methods, a proposal for a DfAM process has been compiled. Design support suitable for use by design engineers is linked to each step in the compiled DfAM process. Finally, the review suggests a possible new DfAM process that allows a higher degree of design automation than today's process. Furthermore, research areas that need to be further developed to achieve this framework are pointed out.

Originality/value – The review maps existing research in design for additive manufacturing and compiles a proposed design method. For each step in the proposed method, existing methods and software are coupled. This type of overall methodology with connecting methods and software did not exist before. The work also contributes with a discussion regarding future design process and automation.

Keywords Design for additive manufacturing, Additive manufacturing, Design optimization, Design automation, Knowledge-based engineering

Paper type Literature review

1. Introduction

Additive manufacturing (AM) is an umbrella term for different manufacturing methods that aim to manufacture complex three-dimensional shapes by adding material successively. Many circumstances, such as usable material, material properties and design constraints, differ depending on the chosen AM technique. Common to most of the techniques is the layer-by-layer approach, which is used during manufacturing. Design for additive manufacturing (DfAM) is a term that has its origin in the term design for manufacturing (DfM), which means designing a part or a product for easy manufacturing (Boothroyd, 1994). DfAM is the category specialized in components manufactured with AM. Compared to most other manufacturing technologies, AM has relatively few manufacturing constraints, which allows for a more optimization driven design process and could result in more valuable components.

Today's design workflows and software tools do not harmonize very well in a DfAM process, and new ones need to be developed as stated by Simpson (Simpson, 2017). The aim of this paper is to review the DfAM research area in terms of methods, design guidelines, and available software. Many different reviews in the area have been performed during recent years (Gao *et al.*, 2015; Yang and Zhao, 2015; Kumke *et al.*, 2016; Laverne *et al.*, 2014; Rosen, 2014; Thompson *et al.*, 2016), and this article contributes a novel design process for AM viewed through the eyes of a design engineer, a proposal for a DfAM process covering each step in the design process including coupling to existing design methods and tools for each step. A discussion of how knowledge based engineering (KBE) could be used to achieve a higher degree of design automation and which tools need to be developed wraps up the review. Aeronautics and metal AM have been the motivators for this study, but the proposed process is generic and is also applicable in other areas.

The paper is divided into five sections. Section 1, Method, describes the method of the performed review. In Section 2, State of the art and classification, a review of existing DfAM classifications and processes is done, where both a new classification and a new design process are presented. Section 3, Existing methods and software, presents a coupling between

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existing methods and software to each step in the proposed DfAM process. Design automation is Section 4, in which an improved process aiming for design automation is discussed. Finally, in Section 5, Conclusion and further work, the paper is summarized and concludes with suggestions for future research in the field of DfAM.

2. Method

The method used in the review consists of six rounds in which literature was sequentially collected, sorted and removed. An overview of the method is shown in Figure 1.

In round 1, different search terms and strings were entered into a search engine (EBESCO, 2017a, 2017b) consisting of the databases EBESCO (2017a, 2017b), Inspec (2017), Scopus (2017), ScienceDirect (2017) and others. The used search terms and the number of results for each term can be seen in Table I.

Rounds 2-4 aimed to go through the results, reduce the amount of literature and sort out the most interesting literature. When relevant literature was sorted out, the focus was to keep research linked to the area of structural components, metal powder bed AM technologies, aeronautic applications, design automation and optimization. Within round 5, snowball sampling was used by investigating references in the chosen literature to find works that had not yet been reviewed. Round 6 was dedicated to the review of commercially available software that supports DfAM.

Most of the references used in the review are from journals, or other types of publications, within the area of manufacturing. In total, publications from many different types of journals and sources have been used. An overview of the categories of publications can be seen in Figure 2.

When identifying the terms to use during the review, some observations were made by trying different search terms and strings in Google scholar. The first observation is for the term *additive manufacturing* that is a stated by ASTM and ISO in 2013 (ASTM, 2013), both before and after several other terms were used. As seen in Figure 3, the terms *rapid prototyping* and *rapid manufacturing* were more common until 2012-2013 when both *additive manufacturing* and *3D printing* surpassed these in number of results.

Another observation was made on the areas within which the most AM research is carried out. Different terms to compare the areas AM, DfAM and design automation for AM were used (Figure 4). In this case the number of results was normalized with the total number of results for each year (a blank search), which would give an indication of how popular the research subjects are. The number of search results indicates a major increase in the area of additive manufacturing and 3D printing that started around 2011 but that has started to stagnate. The number of publications about design for additive manufacturing has not yet stagnated, and the number of publications in the area of design automation for additive manufacturing has started to increase but has not exploded like the other search terms.

Table I Search terms used in the review

Search terms	No. of results
Design for "additive manufacturing"	119
Design optimization "additive manufacturing"	807
Design guidelines "additive manufacturing"	246
Design automation "additive manufacturing"	595

Figure 2 Categorization of the subjects of the sources from which the referenced literature is taken

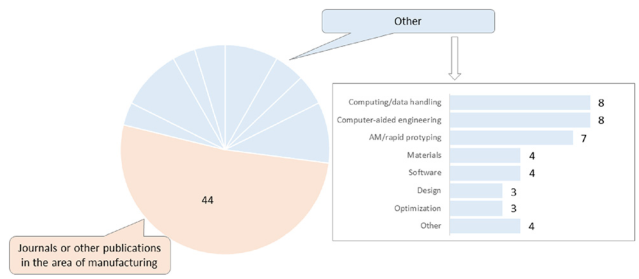
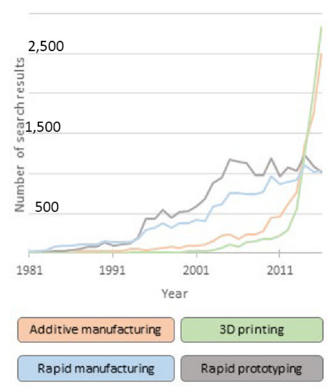


Figure 3 Statics for different kinds of AM research



3. State of the art and classification

Depending on who you ask or what paper you read, the definition of DfAM varies. Several attempts at classifying

Figure 1 Method applied for creating the literature review

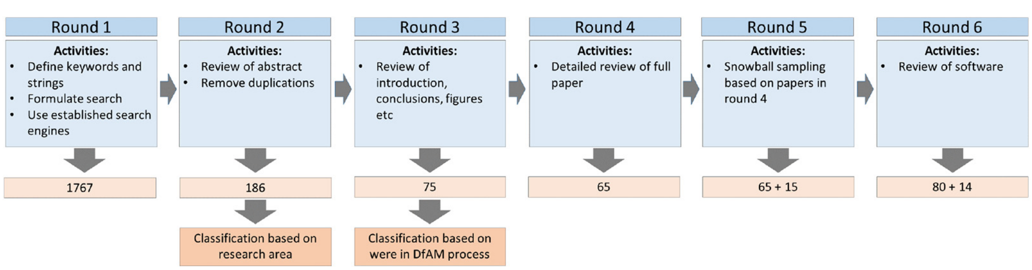
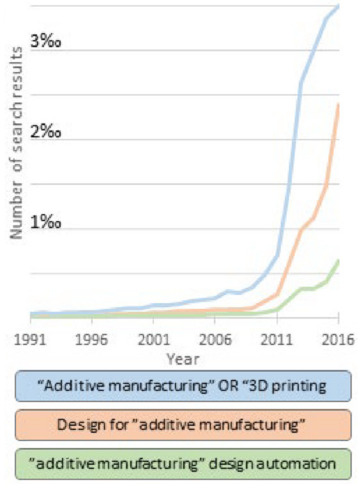


Figure 4 Statistics for terms used in research

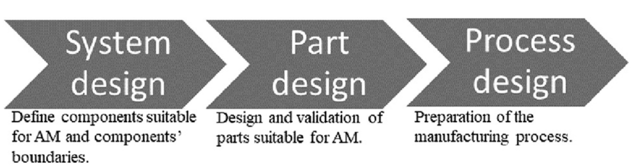


research in the area of DfAM exist (Yang and Zhao, 2015; Laverne *et al.*, 2014; Kumke *et al.*, 2016; Thompson *et al.*, 2016; Rosen, 2014; Guessasma *et al.*, 2015, and Leutenecker-Twelsiek *et al.*, 2016), none of which have focused on the design process itself, and therefore a new process is proposed in this paper.

In this review, three categories are proposed for dividing the DfAM research, namely, *system*, *part* and *process design*. Compared to existing categorizations, these categories have a perspective on the design process and divide up the research based on when and how the research could be useful for a design engineer, designing a product or component for AM. *System design* research is about what should be manufactured using AM and what the component boundaries should look like. *Part design* research tackles how a single part should best be designed, and from a geometrical perspective this category is the most important. *Process design* research involves how design and other preparations of the component for the manufacturing process are best performed. The category is aimed at the design engineer and includes steps necessary for the design work but does not include the manufacturing itself. The categories should be seen as chronological steps where there are formulated goals for each step. However, it is important to state that even if the process design step is the last step, the system and component design categories also involve process-specific details and therefore process aspects are not entirely left to the end of the design process. An overview of the classification can be seen in Figure 5.

The classification has a direct connection to the DfAM process where different activities are connected to each other to create a standardized process. Several generic design methods for AM exist and are extensive to a greater or lesser extent.

Figure 5 Main categories of research in the field of DfAM



Some of these cover part of the design process in detail, while others cover the full design process in less detail. The purpose of the following paragraphs is to give an overview of existing methodologies before a compilation of the existing methodologies in the form of a detailed method covering the whole design process is presented in Figure 6.

Hällgren *et al.* (2016) do not present a design process but discuss how TO could be combined with experience and design rules during the design process. Ponche *et al.* (2014) propose a three-step methodology which starts with identifying build orientation, followed by a TO, and ending with optimization of manufacturing settings. Salonitis and Zarban (2015) expand the design process to a five-step methodology that covers steps from identification and specification of requirements to a multi-criteria decision-making process for identified objectives.

Vayre *et al.* (2012) propose a design process similar to that of Salonitis and Zarban, but add a step of design optimization based on a parametric CAD model after creating an initial design using TO. Orquéra *et al.* (2017) propose a design method based on nine steps with the three main stages Introduction (steps 1-2), Designing with the opportunities and constraints of AM (steps 3-6), and Designing for manufacturing (steps 7-9). The Introduction stage corresponds to the system design category in the classification proposed in this paper, while the remaining steps are within the component design category.

Boyard and Rivette (2014) offer another twist on the design process where DfM is combined with design for assembly (DfA) to better use AM's possibility to include several features in one geometry. Within the DfM part of the design process, it is proposed to use a database with design rules and manufacturing constraints that is automatically evaluated.

Based on the identified design methods and processes above, the generic classification in Figure 5 has been extended to give a more detailed design process as presented in Figure 6. The design process is an interpretation of existing methods, which compared to the existing processes aims to include all steps necessary from choosing AM as manufacturing method of a component to verification of AM capability and preparation for the manufacturing process. Arrows back to earlier steps illustrate an iterative process, which despite the chronological design process is a necessity.

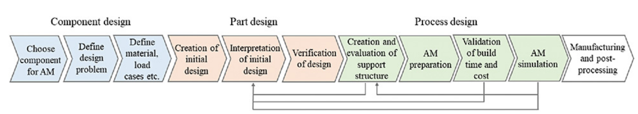
4. Existing tools and methods

In this section, research, methods and tools that support the design process depicted in Figure 6 are presented. The section is divided into one subsection for each step in the design process, where first a review of existing research is presented followed by a table with recommended methods and software tools.

4.1 System design

As presented earlier, system design focuses on the overview of a component and tries to identify when AM is a suitable manufacturing method, what the part boundaries within a

Figure 6 Interpretation of the state-of-the-art DfAM process today



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component and connecting to other components should look like, and which requirements are put on the parts.

4.1.1 Choose component for additive manufacturing.
This step aims to establish which components would in some sense gain from being manufactured using additive manufacturing

Klahn *et al.* (2014) have identified four types of components:

1 components where AM would bring benefits;
2 components where AM could bring benefit but risks and expectations have to be further evaluated;
3 components where no benefits of using AM are expected; and
4 components where AM could not be used as a manufacturing method.

To support the decision-making regarding which products or components should be manufactured using AM, four points where AM creates possibilities to add value to the product compared to conventional manufacturing methods are mentioned. The first is integrated design, where the focus is on reducing the number of parts in the system. Second is the availability for individualization of products or components. The third point is that the manufacturing method enables a more lightweight design compared to conventional manufacturing. Fourth is the possibility to create more efficient designs, based on the fact that a more complex part is not more expensive to manufacture than a simple part (Klahn *et al.*, 2014).

Klahn *et al.* (2015) have continued their work by identifying two different incentives for designing for additive manufacturing, which both have benefits and disadvantages from a business case perspective. The incentives are manufacturing driven design strategy and function driven design strategy. Manufacturing driven design strategy has the advantages of fast production, with no need for special tools or moulds, and the potential for customization. From a business case perspective, these incentives make it possible to use additive manufacturing in a start-up phase and later change to another manufacturing process. This could be a good way if there is a risk that the product will need to be updated based on customer feedback or if an investment in other manufacturing equipment is feasible with an increased manufacturing volume. With a focus on the function-driven design strategy, the incentive is to take full advantage of the freeform and complex shape possibilities offered by AM. By designing for function driven design strategy, a component with a higher value compared to other manufacturing techniques can be achieved. The downside is that the design is locked to a specific AM technique and maybe even a specific machine (Klahn *et al.*, 2015).

Ian *et al.* (2013) apply the ways of adding value to a component or system of components using AM to the E3 concept. The E3 concept is based on three ways to add value to a product: add economic value, add ecological value and add experience value. For AM, economical value could be added through smaller batch sizes and customization. Ecological value could be added by taking advantage of the capability of weight optimization of a component but also less waste material compared to traditional manufacturing methods. Experience value could be added by integrating more or improving the existing functionality of a product.

Agustí-Juan and Habert (2017) have investigated the environmental impact of AM products, drawing the conclusion that the major environmental benefit of using AM is the possibility of reducing material. Built-in functionality would only benefit the environment if it means material could be saved from other systems or if the built function itself improves the environmental impact. The study also includes a recommendation for how to perform a life cycle assessment of AM manufactured products.

The recommended approach for this step is seen in Table II.

4.1.2 Define design problem
When a suitable component is identified where one or more parts will be manufactured using AM, the boundaries between the different parts need to be identified. This also includes defining interfaces with other components, etc.

Compared to traditional manufacturing methods, AM allows for a more integrated design and reduces the number of components in a system. Rodrigue and Rivette (2010) propose a methodology for reducing the number of parts in an assembly process to add value for products when manufactured using AM. The method is divided into nine steps as follows:

1 Design a concept.
2 Draft an assembly of the concept.
3 Determine candidates in the assembly that could be eliminated.
4 Determine if the new design is acceptable.
5 Develop new design alternatives with the reduced assembly.
6 Determine which functions and characteristics could be optimized.
7 Optimization of the functions.
8 Optimization of the characteristics.
9 Select material for the parts in the reduced assembly.

Table II Recommended design methods/tools for step 1 in the compiled DfAM process

Design stage	Recommended design methods/tools
1. Choose component for AM	To identify the right product or component for manufacturing using AM, experience and screening are needed. Investigation and comparison of several different manufacturing methods are also probably needed Klahn *et al.* (2014, 2015) give a guide to which types of components are suitable for AM and which characteristics in a component are beneficial for AM products Ian *et al.* (2013) discuss what type of value AM adds to a component and how that should be used to choose components suitable for AM Chiu and Lin (2016) discuss the possibility to create a virtual business case with combined cost model and design approach

Orquéra *et al.* (2017) suggest an introductory step of DfAM where the function of the system should first be defined and thereafter followed by a kinematic and mechanical analysis. In this step, simple geometric shapes (cylinders, planes, blocks, etc.) should represent the different components in the system. If possible, an optimization of the boundaries between the components should be performed.

Thinking outside the box when setting designing for AM on a system level is something that is highlighted by Emmelmann *et al.* (2011). Different methods for designing on a system level were evaluated and a great potential for system integration is shown.

Bin Maidin (2012) proposes a system design approach where the function is at the centre but is combined with a database consisting of different design features that take full advantage of the AM potential. The database is coupled to different reasons for using AM including user individualization, improved functionality (weight reduction, internal structures, etc.), parts consolidation (e.g. embedded functionality) and aesthetics. By combining them on a system level, the design features could help to improve the product.

Table III shows a recommendation of methods that could be used.

4.1.3 Define material load cases

The goal of this step is to identify requirements and constraints for the part to be manufactured. For this step, the same techniques for analysing the design problem could be used as in ordinary design problems. Examples of methods for this are presented by Ullman (2010) and Ulrich and Eppinger (2012).

What links this step to AM is the choice of material and hard manufacturing constraints. This depends on the AM technique and also on which machine will eventually manufacture the component. An overview of which materials could be manufactured by the different AM techniques is presented in Gao *et al.* (2015). What most AM manufactured materials have in common is that they are anisotropic and both the mechanical properties and surface roughness are dependent on the build direction. Thomas (2009) discusses this aspect in connection with laser powder bed manufacturing.

Manufacturing constraints for AM are dependent on the AM method. One general hard constraint is the maximum build size which is fixed for each machine. Some AM technologies such as direct energy deposition do not have the same strict build size problem, but others such as powder bed fusion have an extremely strict build size (Table IV).

4.2 Part design

4.2.1 Creation of an initial design

The purpose of the initial design is to get an idea of what the part should look like. Depending on the purpose of the part and identified requirements, several different methods could be used. One method that is often used on structural components is topology optimization, which is a good way of creating a design that is optimal for a structural purpose.

In recent years, a lot of research has been put into the development of new TO formulations that take into account different types of AM manufacturing constraints. Using these types of algorithms it may be possible to use the TO design directly for AM or at least create a design that does not need as much redesign between the TO and the manufacturing. However, the focus in the majority of research is on the optimization formulations and mathematics. Instead of reviewing which kinds of optimization formulations exist, this section will focus on how existing commercial TO tools could be used in practice to create designs that are suitable for AM.

Zegard and Paulino (2016) discuss different topology optimization techniques that could be used to combine TO and AM. Some examples of successfully optimized parts that have been manufactured using AM are also shown. Finally, it is highlighted that some manipulation of the TO optimized part is needed before manufacturing in most cases.

Liu and Ma (2016) review how TO could be linked to different manufacturing methods. It is stated that, in most cases, the TO shape cannot be manufactured directly and needs to be manipulated. Automatic smoothing and parametrization of the geometry are mentioned as a desirable approach. Different approaches for achieving this are image recognition or spline based methods. Software for smoothing TO shapes is built into different software. However, it is stated that no software is known that could turn a TO shape into a full parametric CAD model.

Lindemann *et al.* (2015) discuss how TO and design guidelines are best combined for AM. It is concluded that direct use of TO is not possible today, and instead four different alternatives are mentioned and the pros and cons are discussed:

1. Perform TO but remodel it in CAD software.
2. Design a part using design rules and not use TO at all.
3. Perform TO and then interpret the shape using predefined standard CAD features.
4. Combine TO, design rules and standard CAD features.

The first alternative is estimated to be time consuming and it is still not guaranteed that a part this is suitable for AM will be achieved. The second alternative gives a shape this is suitable for AM but may not be optimized. For the third alternative, the results are comparable to the first, but is probably a little faster in the modelling step. The fourth step is the one preferred by Lindemann *et al.* Nevertheless, it is not mentioned how this step will be performed in practice.

Table III Recommended design methods/tools for step 2 in the compiled DfAM process

Design stage	Recommended design methods/tools
2. Define design problem	By using AM instead of other manufacturing methods, the product boundaries could be challenged. More value could be added to the product by combining what would have been multiple components using traditional manufacturing methods into one. This could both reduce the assembly cost and increase the functionality of the product Rodrigue and Rivette (2010) propose a strategy for how to reduce the number of components in an assembly Orquéra *et al.* (2017) present a method for how to define component boundaries within a DfAM process Emmelmann *et al.* (2011) show an example of how redefining system boundaries can increase the value of a product

Table IV Recommended design methods/tools for step 3 in the compiled DfAM process

Design stage	Recommended design methods/tools
3. Define material, load cases, etc.	Within the third step, it is all down to experience and regular engineering work to identify the requirements in the form of thermal requirements, forces and other requirements for each component. Several methods for this exist; one is presented by Ullman (2010) and another by Ulrich and Eppinger (2012) The type of AM machine that is available could limit the number of materials available and material properties. To get an overview of the AM technologies, their pros and cons, and which materials are available, see Gao *et al.*, 2015

Zhu *et al.* (2015) review existing methods for how TO could be used for aerospace design. It is shown how different type of problems that occur in the design of structurally important structures are handled with different TO methods.

Jared *et al.* (2017) discuss that a problem with optimized structures for AM is thin structures that could be manufactured with AM. From a structural optimization perspective, the design could be optimal, but from a design for uncertainties perspective the design is challenging where small deviations in manufacturing could result in huge consequences and be the reason for structural failure. It is ascertained that new methodologies and software need to be developed to address this problem.

Saadlaoui *et al.* (2017) compare different commercial software for TO. The results are compared based on the amount of material needed and the maximum von Mises stress received from the software. The optimized geometries were produced using LBM and the manufactured design was then experimentally tested. Conclusion regarding the different TO software were discussed, but it was stated that more research is needed to conclude which one should be preferred.

Several different software programs for TO exist, and commercial, free and academic TO software are mentioned by the website topology-opt.com (Anon Software list, 2017).

Concluding guidelines for the initial design step are shown in Table V.

4.2.2 Interpretation of initial design

To be able to manufacture the initial design, some kind of interpretation and adaption for AM is often needed. To do this, design rules are used which aim to describe what could be manufactured using AM and what limitations there are. The design rules depend on the additive manufacturing technique, the material used and even the type of machine and the settings for the machine itself. In this section, some of the research in this area is presented. However, it is a complex area with a lot of ongoing research. The presented research has a focus on powder bed manufacturing for metal, and extensive of information is also owned by companies for their specific equipment and cannot therefore be found in the public domain.

Thomas (2009) has carried out extensive research about design rules for SLM and presented different design rules in a report (Thomas, 2009). Adam and Zimmer (Adam and Zimmer, 2013) have developed design rules for SLM, SLS and FDM based on standard elements. Standard elements are geometric shapes described in three different ways: non-curved, simple curved and double curved. For example, a simple plate is non-curved, a cylinder is simple curved where a sphere is double curved. The results are presented in a table with design rules. Adam and Zimmer (2015) have also continued their work with a focus on different building directions and unsupported overhangs.

Unsupported overhangs have also been studied by Atzeni and Salmi (2015), but with a focus on manufactured parts using DMLS. Deviations between the CAD file and the manufactured part were measured to determine the tolerances for different angles of overhang.

Kranz *et al.* (2015) have performed a similar experiment to Adam and Zimmer but with a more specific focus on lightweight structures. The result is a recommendation for how geometries could be designed, visualized in a table.

Rudolph and Emmelmann (2017) present a methodology with corresponding algorithms to automatically compare a component with design rules for SLS and SLM, and to verify that they are fulfilled. The method uses the design rules of maximum part dimension (to fit into the build chamber), minimum wall thickness, gap dimensions, cylinder diameter and diameter of holes. Features connected with build direction (such as minimum build angle) are not addressed by the method.

To create the best design for AM, both restrictions and features that are impossible with other manufacturing methods

Table V Recommended design methods/tools for step 4 in the compiled DfAM process

Design stage	Recommended design methods and tools
4. Creation of initial design	The initial design could be performed in different ways depending on the purpose of the component. To take full advantage of the manufacturing technology it is important to think outside the box and not get stuck on conventional design thoughts For structural components, topology optimization is recommended. Topology optimization for fluid dynamics is also available and could ideally be used to get inspiration for e.g. internal cooling. The website topology-opt.com (Anon Software list, 2017) lists commercial, free and academic TO software. Saadlaoui *et al.* (2017) compare different commercial TO software and make comments on which to use. Zhu *et al.* (2015) review how TO could be used for aeronautic design and show example of good practice For non-structural or fluid dynamic based structures, the method presented by Bin maidin (2012) could be used. The method is based on using standard features that use the advantages of AM

must be considered. One such feature is lattice, cellular or grid structures which reduce the weight of a structure while preserving good mechanical properties. With traditional manufacturing methods it is difficult to create such structures integrated in components, but this is possible when using AM (Wang *et al.*, 2013).

Lattice structures could be divided into three categories: disordered, periodic and pseudo-periodic. Disordered structure are randomly distributed structures spread over a design, periodic structures use a standard cell that is evenly distributed over the design and pseudo-periodic structures use a standard cell that is adapted to the shape of the design. The periodic and pseudo-periodic lattice structures could both be heterogeneous and homogeneous. In homogeneous structures the standard cells have the same size everywhere in the design, while in heterogeneous structures the standard cell can vary in size (Tang *et al.*, 2015). Examples of different standard cells, a comparison between them, and a discussion of when to use which are discussed in Tang *et al.* (2015) and Beyer and Figueroa (2016).

Two methods for designing lattice structures are presented by Zhang *et al.* (2014). The first method is based on a parametric optimization where a standard cell's density is optimized using parametric optimization. One parameter for each cell in the design is needed, which creates a large and difficult optimization problem. The second method uses a variable density topology optimization and from that a lattice structure is designed.

Parametric design optimization combining a CAD model with a finite element (FE) model is shown by Gorguluarslan *et al.* (2017) and Salonitis *et al.* (2017). Paz *et al.* (2016) use a similar method but supplement the FE model with surrogate modelling to perform more design evaluations. A method for creating lattice structures from TO is presented in (Robbins *et al.*, 2016). This method uses several topology optimizations with different densities which, in the final design, are represented by graded density lattice structures.

Several problems and challenges with using AM manufactured lattice structures are mentioned by Wang *et al.* (2013). These include the fact that the relatively rough surfaces of AM manufactured components can have a large impact on thin lattice structures and the removal of non-manufactured powder from the lattice structure (when powder bed fusion technologies are used). For laser methods, the removal of powder is easier than the removal of pre-sintered powder from electron beam manufacturing. Another problem with combining lattice structures with AM is the small and many surfaces that occur within the lattice structure which are difficult to represent in a good way with the STL file format (as used by most AM machines). STL represents the design using triangles on the surfaces, the small scale of the lattice structure makes it difficult to generate, and a small error in the data file may have a significant impact of the structural strength of the design (Robbins *et al.*, 2016).

Concluding recommendations when interpreting the initial design are seen in Table VI.

4.2.3 Verification of design

The verification of design is similar to the design process for other manufacturing processes, and this includes CAE analyses for the verification of structural, thermal, aerodynamic and other properties. Two things that are unique to CAE analyses for AM parts are the possibility to create more complex structures such as grid structures and the anisotropic material behaviour which make it more complex to simulate compared to isotropic materials.

The surface roughness for an AM manufactured part is dependent on the geometry and the build direction. This makes it difficult to simulate from thermal, fluid dynamics and aerodynamic perspectives that are dependent on the surface. From a structural perspective, mechanical properties such as Young's modulus, yield strength and fatigue resistance are crucial. These properties are also influenced by anisotropy and are therefore difficult to simulate. Dordlofva and Törlind (2017) address where knowledge is lacking to verify components for the space industry.

Most of the main CAE software programs such as Abaqus, Dassault Systemes (2018) and Ansys (2018) have incorporated solvers for anisotropic materials into their suites of CAE products. However there is a need for greater knowledge and experience to obtain correct calculations.

This information is also presented in Table VII.

4.3 Process design

The process design category comprises research that aims to describe how the design is prepared for manufacturing. Liu and Rosen (2010) divide process design into the three steps: part orientation, slicing scheme and process variable optimization. Jin *et al.* (2017) add the steps support generation, path generation and post-processing into the definition of AM process design. The choices made will affect what the best design of the component (and possibly the system) will look like, and iterations are therefore necessary.

Exactly which steps should be incorporated into the process design step could be argued, but in this review all steps from design to manufacturing are discussed. In this review the three

Table VI Recommended design methods/tools for step 5 in the compiled DfAM process

Design stage	Recommended design methods/tools
5. Interpretation of initial design	No commercial CAE tool is available for transforming initial shapes into shapes suitable for AM, hence traditional CAD programs have to be used To be ensure suitability for AM, different recommendations of how to design for AM exist. The tables with design recommendations presented by Thomas (Thomas, 2009) and Adam and Zimmer (Adam & Zimmer, 2013) are recommended. Kranz *et al.* (Kranz *et al.*, 2015) present similar design recommendations but are more specific on lightweight structures Two different methods of how to create lattice structure design are presented by Zhang *et al.* (2014). Design of a lattice structure is supported by Netfabb (Autodesk, 2017) and Materialise (Materlise NV, 2017)

Table VII Recommended design methods/tools for step 6 in the compiled DfAM process

Design stage	Recommended design methods/tools
6. Verification of design	The purpose of the step verification of design is to validate the structural (and other properties, such as fluid dynamics) performance of the component. Dordlofva and Törlind (2017) discuss the challenges of verification of AM produced parts No special CAE tools for the verification of AM parts exist. Instead, different commercial CAE tools such as FEA or CFD software are recommended for this step. Examples of FEA solvers that can handle anisotropy include Abaqus (Dassault Systemes, 2018) and Ansys (2018)

categories *support structure*, *manufacturing settings* and *AM simulation* of manufacturing are chosen.

4.3.1 Creation end evaluation of support structure

For metal powder bed fusion, AM support structure needs to be added in overhang regions. The added support structure adds extra material in the manufacturing which adds manufacturing time, waste material and post-processing time for the removal of the structure. The overhang regions and the addition of support structures also create worse surface structures compare to other areas (Hu *et al.*, 2015). To reduce the support needed for manufacturing a component, there are three alternatives: optimization of the shape and placement of the support structure, optimization of the build direction and changing the design to make the component self-supporting.

Support structure is directly linked to the choice of build direction during manufacturing. Leutenecker-Twelsiek *et al.* (2016) point out the importance of an early decision on part orientation for a component manufactured using AM. The motivation is to enable the use of design rules and recommendations which allow for the creation of self-supporting components and minimize the amount of support structure. Automated methods for choosing the best build direction to minimize the amount of support structure are presented in (Strano *et al.*, 2013a, 2013b) and (Zwier and Wits, 2016). Das *et al.* have combined different manufacturing objectives for multi-objective optimization. In one study, minimization of the amount of support structure and minimization of the error of the manufactured part because of staircase effect (Das *et al.*, 2015) are performed. In another study, the amount of support structure and build time are minimized (Das, 2016).

The creation of a support structure could be performed in different ways and is often based on some mathematical algorithm that analyses the geometry in combination with the build direction. Challenges in the creation of a support structure include identifying areas that need support, minimizing volume of support, giving the support sufficient mechanical properties (structural strength and heat dissipation), and providing support that is easy to remove. Examples of research in the area include (Jared *et al.*, 2017; Zhang *et al.*, 2014; Tominski *et al.*, 2018; Wang *et al.*, 2013; Tang *et al.*, 2015; Tang *et al.*, 2018; Beyer and Figueroa, 2016; Robbins *et al.*, 2016; Koch, 2018).

Tools for the evaluation of support structure are presented in Table VIII.

4.3.2 Additive manufacturing preparation

The AM preparation step is about setting up the machine before the manufacturing is performed. This includes manufacturing settings which are highly relevant for the result of a part manufactured with AM. However, it is difficult to give an overview of the subject and general guidelines do not exist. The type of settings that are available depend on which machine and which software for controlling the machine are used. Which settings are optimal also depends on the material, the geometry and whether other components are built at the same time.

The manufacturing settings could be divided into four types: energy-related, scan-related, powder-related and temperature-related. Energy-related settings include the power of the energy source, spot size, pulse duration and pulse frequency. Scan-related settings include scan speed, scan spacing and scan pattern. Powder-related settings are linked to the material used and include particle shape and size, as well as how the powder is distributed and which layer thickness is used. Temperature-related parameters include the temperature of the powder bed, feeder and the uniformity of the temperature. All parameters are strongly dependent on each other and changing one will affect the other parameters as well (Gibson *et al.*, 2010).

Table VIII Recommended design methods/tools for step 7 in the compiled DfAM process

Design stage	Recommended design methods/tools
7. Creation and evaluation of support structure	The creation of support structure could be performed manually in CAD or in an AM preparation software. The amount of support structure is directly linked to the build direction and the geometry. When and how the build direction should be chosen is discussed in Leutenecker-Twelsiek *et al.* (2016), Strano *et al.* (2013a, 2013b), Zwier and Wits (2016), Das *et al.* (2015) and Das (2016) AM preparation software could be used for the automated addition of a support structure based on geometrical considerations of the model. Examples of commercial software with AM integration are Netfabb (Autodesk, 2017), Siemens NX (Siemens AG, 2017), Materialise Magics (Materlise NV, 2017), Simplify3D (Simplify3D, 2017) and 3D systems (3D Systems, 2017) Dassault Systems are also interested in the area of AM and are about to launch software within the area (Dassault Systems, 2017) In addition, there is printer-specific software for different AM techniques and free software with similar functions. Examples of such software are Makerbot Print (Makerbot Industries, 2017), Cura (Ultimaker, 2017) and Preform (Formlabs, 2017)

Most AM manufacturing companies use standard settings for different materials and machines, and it is therefore difficult for the design engineer to change the settings. Instead, the most common way is to change the design if errors occur in the manufacturing. In an ideal future, the design process will include a feedback loop where the geometry and manufacturing settings are controlled together to achieve an optimization for the whole system.

Some final comments about this step are made in Table IX.

4.3.3 Validation of build time and cost

An estimation of the build time for a part is crucial to be able to calculate the cost of manufacturing. In the area of cost simulations for additive manufacturing, Costabile *et al.* (2017) have performed an extensive review of different research and have concluded that no matter which AM technique is used, the cost model looks similar. A couple of different models are highlighted and presented in more detail in Costabile *et al.* (2017). Chiu and Lin (2016) have investigated the possibility of producing a simulated business case to define whether or not a product is suitable for converting to AM, including a cost model combined with DfAM to optimize the cost based on the design and the production technique.

Table X contains concluding words about this step.

4.3.4 a.m. simulation

Different approaches have been used in both research and commercial software for simulating the process of AM and which result will be achieved in terms of productivity, surface quality and dimensional accuracy of the final part. Bikas *et al.* (2016) have divided the simulation approaches into three categories, analytical, numerical and empirical, based on which principle is used. The analytical simulation models are based on physical laws which have the advantage that they can easily be adapted to different processes, machines and machine settings. However, they are limited by the initial assumptions that need to be made to use the laws of physic. The empirical approach is based on testing and is therefore accurate for the exact test set-up, but is more difficult to adapt to other machines and set-ups. The numerical approaches try to combine the two other approaches and start with an analytical model which is combined with a numerical model. An overview of the research within the field of AM process simulation is compiled in Bikas *et al.* (2016) and is shown in Table XI.

A good overview of the research into simulation models for residual stress in components manufactured using LBM is also given by Patterson *et al.* (2017).

The commercial software that exists for simulating the AM process is shown in Table XII.

5. Design automation in design for additive manufacturing

The state of the art DfAM process presented in Figure 2 shows a sequential flow with manual work and rework that must be performed if later steps do not fulfil the requirements. An alternative is to create a more automated framework that would allow a faster product development process. To achieve design automation in the DfAM process, the iterative work after the creation of the initial design needs to be automated. A proposed framework that uses the same steps as presented earlier but using design automation is shown in Figure 7.

The framework presented in Figure 7 is something we propose and has not yet been implemented. Part of the framework was implemented in a case study where topology optimization, support structure evaluation and an FEM model for calculating stress were combined in a multidisciplinary framework (Wiberg *et al.*, 2018). In the automated DfAM process, the same tools and methods are used as presented in Section 4 – existing tools and methods, but by introducing automatic knowledge transformations between the disciplines, a smarter system could be created.

The proposed framework is a type of knowledge based engineering (KBE) system and works as a framework with the goal of automating non-creative tasks and preparing for multidisciplinary design optimization (MDO) (Rocca, 2012). Part of the framework, such as material knowledge and manufacturing requirements, could be reused for several types of components while others, such as geometry and CAE models for component verification, need to be changed when a

Table IX Recommended design methods/tools for step 8 in the compiled DfAM process

Design stage	Recommended design methods/tools
8. AM preparation	For the AM preparation step, the same software list as in step 7 is recommended. There are no general guidelines for determining what type of setting to use. The settings are specific to each machine, material and desired type of characteristic of the build. For more information in this area, see (Gibson *et al.*, 2010)

Table X Recommended design methods/tools for step 9 in the compiled DfAM process

Design stage	Recommended design methods/tools
9. Validation of build time and cost	All of the software mentioned in step 7 gives an indication of the print time based on the geometry set-up and the AM preparation settings. If no AM preparation software is available, the build time could be predicted using different models. Chiu and Lin (2016) show an example of this The cost of a product is more challenging. This depends on the material, build time, number of components in the build, etc. Methods for calculating the cost of an AM manufactured component are shown in a review performed by Costabile *et al.* (2017)

Table XI Overview of research in the area of simulation models of AM processes

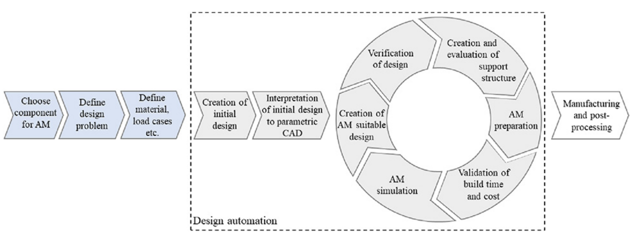
Type	Surface roughness	Dimensional stability	Mechanical properties	Heat transfer	Melt pool
LBM	Strano *et al.* (2013a, 2013b)	Chen and Zhang (2006), Raghunath and Pandey (2007)	Dong *et al.* (2009), Liu *et al.* (2012), Khairallah and Anderson (2014), Matsumoto *et al.* (2002)	Wang and Kruth (2000), Chen and Zhang (2010), Dong *et al.* (2009), Shen and Chou (2012a), Liu *et al.* (2012), Kolossov *et al.* (2004), Michaleris (2014), Matsumoto *et al.* (2002), Lee *et al.* (2017)	Chen and Zhang (2010), Hu and Kovacevic (2003), Nurul Amin (2012)
EBM			Gockel *et al.* (2014)	Gockel *et al.* (2014), Shen and Chou (2012a, 2012b)	Markl *et al.* (2013), Ammer *et al.* (2014)

Source: Adapted from Bikas *et al.* (2016)

Table XII Recommended design methods/tools for step 10 in the compiled DfAM process

Design stage	Recommended design methods/tools
10. AM simulation	Exactly when and how simulation software for the process should be used is something that has not been established in research, but from personal experience the software companies recommend using it with a trial and error approach to gain knowledge about how good the part will ultimately be The following computer software can predict stresses and deformation of a part during manufacturing: Netfabb (Autodesk, 2017), Siemens NX (Siemens AG, 2017), Materialise Magics (Materlise NV, 2017), Simplify3D (Simplify3D, 2017), 3D systems (3D Systems, 2017), 3Dsim (3Dsim, 2017), Simufact Additive (MSC Software, 2017)

Figure 7 Proposed design automation framework



new component is developed. What the multi-objective optimization problem formulation should look like still needs to be determined. Objectives in the optimization could be minimizing mass, minimizing cost and/or minimizing deformation and internal stresses during manufacturing. Some of the requirements are strict (such as maximum stresses in the component and hard manufacturing constraints), while others (such as minimizing the amount of support) are more a matter of wishes and could be treated as either constraints or objectives. Central to this framework is a flexible parametric CAD model created based on the initial shape. To achieve design automation, an automated process for the creation of the parametric CAD is desirable. The parametric CAD should be able to take the shape of the initial design but also be changeable and adaptable based on feedback from the different CAE tools.

Some studies with similar ideas or implementation have been performed by others. Baumers and Özcan (2016) discuss the creation of a framework that is similar to the proposed design automation framework but is not detailed in terms of which CAE tools and steps are necessary. Research that implements the ideas of parts of the proposed framework has been found, but nothing that covers the entire process and all the disciplines. Implementation of frameworks and algorithms for minimizing the amount of support structure is shown in the literature. A method for automated build orientation of a part based on minimizing support structure is discussed by Zwier and Wits (2016). Hu *et al.* (2015) have developed a framework for minimizing the amount of support structure by using shape optimization that manipulates a component to make it self-supporting. The research shows that there is great potential when starting with one shape and that, by manipulating it, it is possible to drastically reduce the amount of support structure.

Manufacturing constraints and their automated handling are discussed by Rudolph and Emmelmann (2017). An algorithm for automated checking of whether a CAD model fulfils AM design restrictions such as minimum wall thickness and gap thickness has been developed. A similar approach could be linked to an optimization and could penalize alternatives that do not fulfil the AM manufacturing criteria. Ranjan *et al.* (2017) show how a manufacturability index could be used to measure how well a component could be manufactured by using LBM. The index is automatically calculated based on a CAD model. By optimizing the index, the number of support structures needed and other details that are difficult to manufacture using AM were reduced. The method could be used in combination with both parametric and topology optimization of a component. Reuse and automated handling of process settings and parameters in a KBE system are also discussed by Liu and Rosen (2010).

6. Conclusions and further work

The paper has reviewed over 1,500 publications in the area of design for AM, design automation for AM, and optimization and AM. Using a structured method, the publications have sequentially been filtered down and ultimately an elaborated review based on over 100 papers has been compiled. Within the review, the publications have been divided into categories based on when in a design process the research could best be used.

Based on the review, a new detailed DfAM process has been proposed together with a mapping of available design support in the form of methods, design rules, guidelines and software tools. Furthermore, recommendations are given for which types of tools and methods are best suited at the different stages of the design process.

Finally, the review proposes a new type of design process for additive manufacturing which aims to achieve a more automated design process for AM. The framework shows the potential for reducing the iterative work within the design process. The proposed design automation process is presented on a generic level and is connected to existing literature. However, to achieve design automation in practice, further work is necessary, namely:

- Developing methods for the transformation of an initial design into a parametric CAD model suitable for design automation. The model should be flexible enough to be used and manipulated together with other CAE models and tools.
- Automatic coupling of different AM specific simulation models and tools such as support structure creation and evaluation, manufacturing setting, manufacturing simulation, cost simulations, etc.
- Formulating MDO problems with a specification of the most suitable objectives and how constraints should be formulated and handled to achieve an overall optimal design.

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