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Design for additive manufacturing: Review and framework proposal

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Abstract

Additive manufacturing (AM) technologies have seen fast growth in the last few decades. AM needs the implementation of new methods in design, fabrication, and delivery to end-users. Hence, AM techniques have given great flexibility to designers as the design of complex components and highly customized products are no longer binding from a manufacturability point of view. In addition to high material variety, this allows multi-material and variable mechanical characteristics of product manufacturing. This review paper addresses the design for additive manufacturing (DfAM) rules, guidelines, and tools to guide the designer to take advantage of the opportunities provided by AM whether in the early design stages (EDS) or in the later phase using computer-aided design (CAD) tools. It discusses issues related to the design for AM and proposes a DfAM framework applied in the design for the additive manufacturing process.

Keywords: Design for additive manufacturing (DfAM), Additive manufacturing (AM), Design optimization, Design rules, Design guidelines, DfAM tools

1. Introduction

Different additive manufacturing (AM) techniques [1], aiming to manufacture complex three-dimensional shapes by adding material layer by layer successively, are in fast growth [2]. Design constraints differ depending on the chosen AM technique [3]. As designing a part or a product for the ease of manufacture is the definition of the idiom design for manufacturing (DfM) as introduced by Boothroyd et al. [4] The term design for additive manufacturing (DfAM) derived from it would the category specific to components produced with AM [3]. Pradel & Rennie [5] adopted "the use of design thinking to help identify, validate and communicate high-value propositions enabled by additive manufacturing" as a definition of DfAM. DfAM is a multi-faceted problem, incensed by constraints to creativity, knowledge propagation, lack of education, and a discontinuous software pipeline. Indeed, Saliba et al. [6] reported that there are three fundamental problems that intersect with DfAM: i) software to support efficiently DfAM needs; ii) design engineers require a fresh perspective enhanced by increased creativity and knowledge; iii) a paradigm shift in education is needed to pervade engineering graduates with comprehensive AM knowledge. This AM knowledge encompasses DfAM rules, guidelines, and tools that need to be understated and applied correctly. Indeed, Durakovic [2] identified the DfAM knowledge as the biggest challenge of AM especially since cognitive barriers and past practice with traditional manufacturing techniques will have to be overcome with these new ones.

This paper aims to review the DfAM research area in terms of design rules, design guidelines, and available tools to contribute to building knowledge in this field. Several different reviews in the research field have been carried out during recent years [3, 13, 14, 18] and this article contributes to building knowledge by gathering designs for AM rules, guidelines, and best practices that could be useful for an engineering designer. DfAM tools covering each step in the design process including the early design stage (EDS) and detailed design stage, are collected. A discussion of how this knowledge could be used to achieve a higher degree of design efficiency and which tools need to be developed wraps up the review.

This paper is divided into four sections. Section 1 is reserved for an introduction where the research gap was presented. In Section 2, a review of existing DfAM rules, guidelines, and best practices is done. Section 3, presents a classification of available DfAM tools according to the design process stage: CAD phase tools and EDS tools. Finally, in Section 4, a discussion is made and conclusions with suggestions for future research in the field of DfAM are noted.

2. Design for additive manufacturing

2.1. Design for AM rules

Walton and Moztarzadeh have collected designs for Electron Beam Melting (EBM) rules and guidelines, which are mostly similar across a majority of AM technologies [7]. Rules, that are basic knowledge in order to design a successful additive-manufactured product, are listed hereafter:

- Do not outstrip the size limits of the equipment.

The designer should refer to the manufacturer datasheet or to an AM machine information database (Figure 1) like the one created by Liu et al. [8]

Technology	Manufacturer	Model	Build volume (mm^3)	Layer thickness (mm)	Material	Dimensional accuracy (mm)	Tensile strength (MPa)	Yield strength (MPa)	Flexural strength (MPa)	Elongation at break (%)
FDM	Stratasys	Fortus 450c	406 × 355 × 406	0.13-0.33	Polylactic Acid	0.06	37	n/a	62	4.4
Metal FDM/ Material extrusion	Markforged	Metal X	300 × 220 × 180	0.05-0.20	Fibre glass	0.20	590	n/a	210	3.8
SLS	EOS	P396	340 × 340 × 600	0.06-0.18	Polyamide (PA2200)	0.10	50	n/a	52	20
SLS	3D Systems	sP230	550 × 550 × 750	0.08-0.15	Polyamide (DuraForm PA)	0.10	43	n/a	48	14
SLM	Renishaw	AM250	250 × 250 × 365	0.02-0.10	Stainless steel 316 L	0.07	607-678	480-550	n/a	27-45
SLM	SLM Solutions	SLM 280	280 × 280 × 365	0.02-0.075	Inconel 718	0.06	954-1034	637-767	n/a	23-25
EBM	GE Arcam	A2X	200 × 200 × 380	0.05-0.15	Ti-6Al-4V	0.20	1020	950	n/a	14
MJP	3D Systems	Projet 860Pro	508 × 381 × 229	0.10	VisiJet PXL composite	0.26	26.4	n/a	44.1	0.21

Notes: Fused Deposition Modelling (FDM), Selective Laser Sintering (SLS), Selective Laser Melting (SLM), Electron Beam Melting (EBM), MultiJet Printing (MJP), n/a in here means the data is not published by the manufacturer. In the methodology, if the relevant data is n/a, it is considered to be adequate

Figure 1. Commercial AM machines information: extract of Liu et al. database [8]

- Privilege self-supported structures in order to reduce the number of support structures that have to be removed in post-processing.

Indeed, self-supporting designs eliminate the need for structural support. Usually, 45° is the minimum overhang angle requisite to ensure that designs could be fabricated without requesting any supporting structure. However, this is material and AM process-manufacturing parameters dependent. The minimum self-supporting angles as recommended by Smith and Storey are approximately 30° for stainless steels, 55° for Inconel, 30° for titanium, 45° for aluminum, and 30° cobalt and chrome [9]. It should be noted that several researchers are working on the self-supporting topology optimization for additive manufacturing and that the results found are promising to support the designers in their eco-design approach [10, 11, 12].

- Non-circular holes are preferred if there is no technological constraint.

If the hole is not a functional entity, teardrop-shaped holes are recommended, as they will not require any support structure but can still offer the same material-saving benefits [12].

- Supports, to be removed, are expected to damage the surface of the product. Therefore, be vigilant that anchoring points or overhanging surfaces will have a limited surface quality.

Additional support structures are frequently needed, which leads to time, material, and energy waste [13]. Support structures are usually optimized with the aim to minimize material usage, and, consequently, minimize the cost and build time of the AM-produced part. Cellular support structures are suitable as they have a low solid volume fraction, shorten build time, and reduce the needed time for support structure removal. The main support methods have been collected by Jiang et al. [13] for visual perception (Figure 2). Without omitting the fact that the support structure volume, building time, and production cost are functions of the build orientation. For simple parts, the build orientation is typically identified directly by the designer; however, for complex ones building orientation optimization needs to be done [14].

- Do not create fully-enclosed cavities or hollows to be able to eliminate the extra powder.
- Envisage accesses for post-processing tools required for support removal.
- Avoid large masses of material.

The designer can intervene at the level of the material choice (lighter material), at the level of the support structure, or at the level of the material structure by applying the lattice generation technique. Jiang et al. [13] categorized the different support forms (Figure 2) correspondingly with the AM technique. Lattice supports are suitable for the metal AM process while cellular support and “Y”, “IY”, and pin support are appropriate for the SLM technique. Honeycomb support, sparse tree support, tree-like support, space-efficient branching support, grain support, and bridge support are convenient for the FDM technique. The unit cell support could be used for all processes.

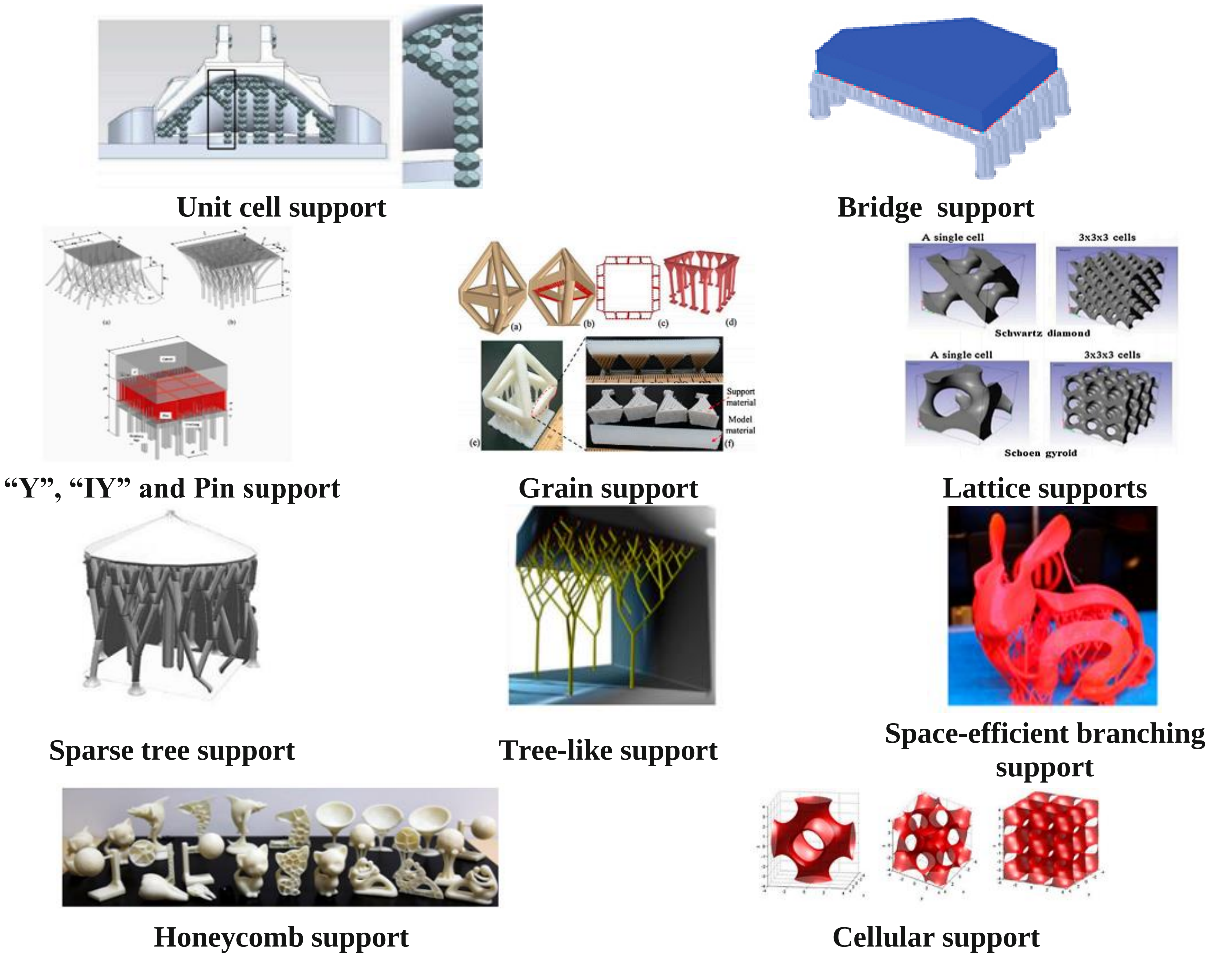


Figure 2. Main support methods [13]

- Be vigilant about the minimum feature size for a given AM system or material and the clearances between moving parts.

Diegel et al. [15] mentioned that the minimum hole (or slot size) is related to the thickness of the part, the print orientation, the layer thickness, as well as the used AM machine. Similarly, for the clearances between moving parts; the bigger the surface area of the components that are in close contact, the bigger the gap between the moving parts should be.

- The decision to manufacture a part by AM technologies should depend on its complexity.

From a cost point of view, it would nearly frequently be more economical to produce geometrically simple parts using conventional technologies if they are quicker than AM [15]. Therefore, it could be wise to consider CNC machines and hybrid machines as alternatives during the manufacturing machine selection.

- Availability of material

Designers need to be enlightened if the product material is available and under which form: powder, filament, or resin. Most frequently used metals, such as stainless and maraging steel, titanium, aluminum, chrome, cobalt, and nickel-based alloys could be available. Most machine and filament manufacturers are offering the non-metals: Acrylonitrile butadiene styrene (ABS), Polylactic acid (PLA), nylon, polycarbonate, and polypropylene.

- Be aware of the longest printable bridge length (LPBL) which is the longest length the AM machine can build (with fulfilled finish quality) without a support structure to hold it. This LPBL is print temperature, solidification speed, and print speed dependent (Figure 3).

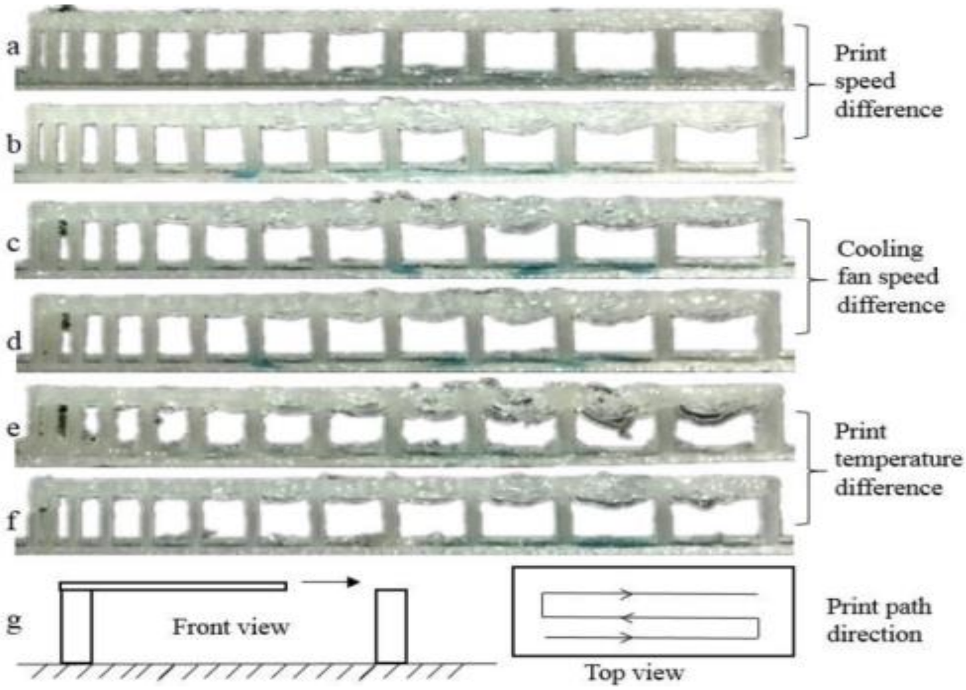


Figure 3. Longest printable bridge length [16]

2.2. Design guidelines for AM

In this section, the authors will mainly refer to the guidelines suggested by Walton & Moztarzadeh [7] for EBM, however, that could be generalized for most of the AM technologies and we will enhance them with other guidelines resulting from other researchers' work. Specific design guidelines depending on the component geometry, the intended use, the production volume, and the AM technology could be added.

- Optimize the component orientation at the design stage with the goal to minimize the requirement for support.
- Afford material overstock to high tolerance surfaces so that it can be removed by an adequate post-processing process (CNC machining or Electrical Discharge Machining-EDM) that guarantees the desired surface finish (roughness and flatness).

- During the design stage, forecast tooling access for an easy powder removal from internal geometries, which could be difficult due to the partially sintered material or the flow behavior of powder.
- Shun thin vertical structures, since they risk breaking if whacked by the powder rake. Consider re-orientating the part within the build chamber or enlarging the footprint area of the component; if thin vertical structures cannot be avoided.
- Shun sharp edges or corners to avoid stress concentration, distortion, and peeling from the build plate
- Consider assembly consolidation and manufacture in-situ to minimize, even eliminate, assembly time and simplify the supply chain.
- Afford line-of-sight access to all surfaces requiring finishing processes (shot peening, EDM, etc.)
- Reduce variations in section thickness to avoid warping due to differing thermal gradients nearby the melt pool
- Validate the mechanical properties of a selected material for a chosen AM system and process parameters

Jiang et al. [13] recommended paying attention to the support structures design, which should be based on the following guidelines:

- The support should be able to prevent parts from warping/collapsing, especially the outer contour area that needs support. When designing supports for metal processes, it is recommended to take into consideration induced stresses and strains and to conduct thermal simulation modeling.
- Minimize the strength of the connection between the support and the final part. A compromise should be made, strong enough to perform the support function and not too strong to be easily removed.
- The contact area between the final part and the support should be as tiny as possible to reduce surface damage after support removal
- Build time and material consumption should be considered as major factors underway in the support design process. The trade-off between them and the final product quality has to be considered.

Diegel et al. [15] have also identified general guidelines for designing AM parts. An additional guideline is, then, added to the previous ones:

- When designing for AM, the designer should constantly design around the specific orientation in which the component will be printed since part orientation will govern the direction of anisotropy, the roundness of holes, surface finish, and support material.
- Consider the bionic design and the temporal DfAM.
- Inspired by utero human development, Saliba et al. [6] proposed a novel approach to increase creativity in DfAM through the time domain. The temporal DfAM (TDfAM) approach offers a drastically new way of conceiving the design of AM materials. The authors develop an open-source CAM program that allows varying the toolpath angle and the extrusion speed throughout the manufacturing time. They highlighted that it is widely accepted that AM processing parameters modify the properties of AM materials. Hence, the final material product of TDfAM will be spatially dependent.

In the aim to solve conflicting issues on design for remanufacturing, Kandukuri [17] build a set of design guidelines based on a TRIZ matrix applied to the case of remanufacturing for additive manufacturing. By means of several reviewed research publications, Kandukuri collected AM design guidelines that are relevant for remanufacturing (Figure 4).

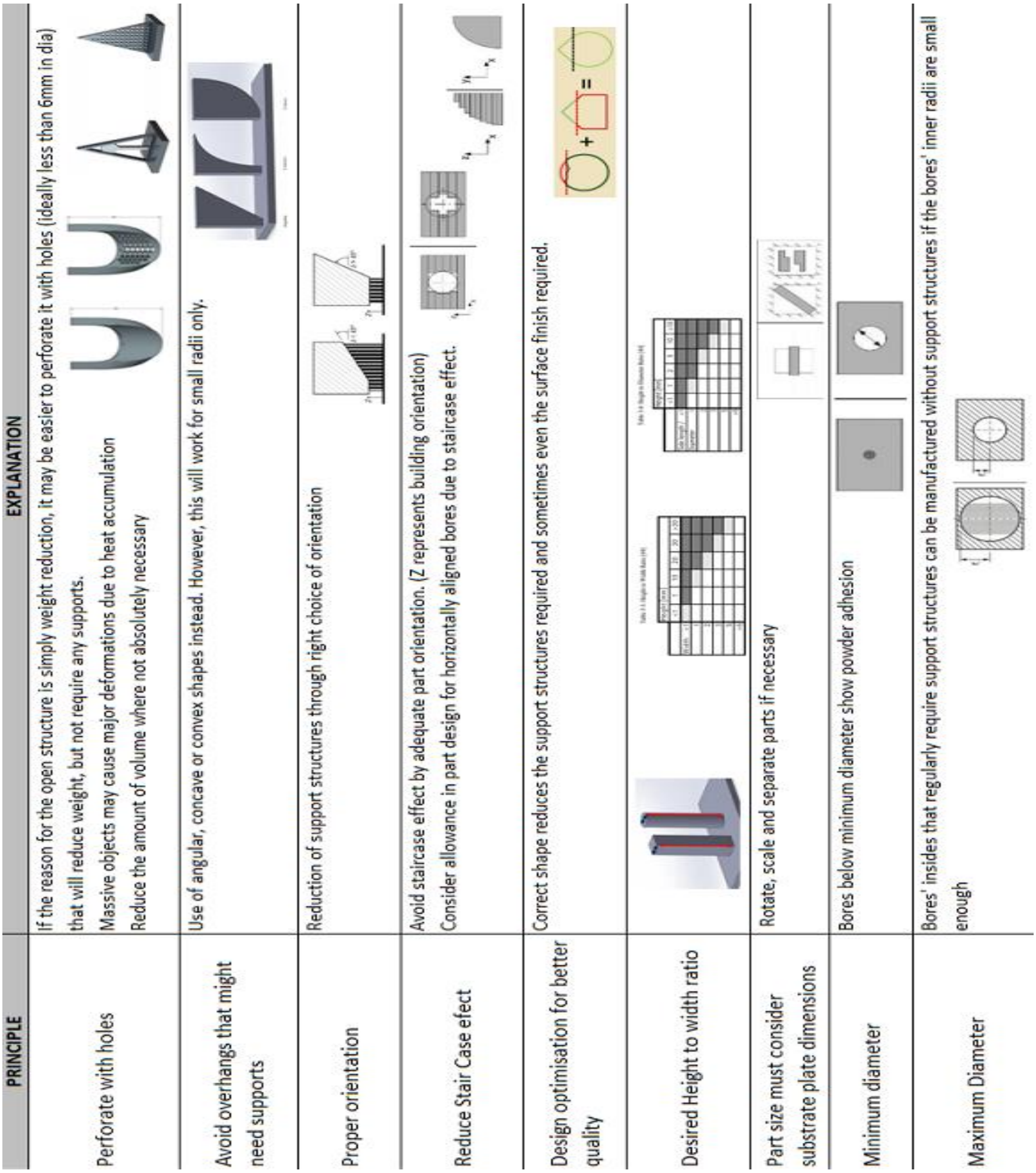
2.3. Good practice and recommendations

- Initially maximize the design domain (volume which can contain part geometry) to improve the topology optimization outcome by beginning with the build volume of the AM machine and then removing the interaction of other components in an assembly [7]
- EBM should be limited to high-performance applications where the functionality of a component is of greater effect than the manufacturing cost [7].

- Round all sharp edges since it makes the artifact more ergonomic and comfortable to hold and use without risks of sharp edges, and it decreases the stress concentrations [15].

3. DfAM tools

Increased emphasis on life-cycle sustainable products and the pursuit of greater efficiency especially lower energy consumption has driven the research into developing lightweight and robust designs. Topology optimization (TO) and lattice generation have emerged as the two main light weighting strategies, best exploiting the design freedoms provided by AM. These two tools could be used in the CAD phase nevertheless in the earlier design stage (EDS); tools that are more intuitive could be used such as DfAM Worksheet and LiDS Wheel.



PRINCIPLE	EXPLANATION
Perforate with holes	If the reason for the open structure is simply weight reduction, it may be easier to perforate it with holes (ideally less than 6mm in dia) that will reduce weight, but not require any supports. Massive objects may cause major deformations due to heat accumulation. Reduce the amount of volume where not absolutely necessary
Avoid overhangs that might need supports	Use of angular, concave or convex shapes instead. However, this will work for small radii only.
Proper orientation	Reduction of support structures through right choice of orientation
Reduce Stair Case efect	Avoid staircase effect by adequate part orientation. (Z represents building orientation) Consider allowance in part design for horizontally aligned bores due to staircase effect.
Design optimisation for better quality	Correct shape reduces the support structures required and sometimes even the surface finish required.
Desired Height to width ratio	
Part size must consider substrate plate dimensions	Rotate, scale and separate parts if necessary
Minimum diameter	Bores below minimum diameter show powder adhesion
Maximum Diameter	Bores' insides that regularly require support structures can be manufactured without support structures if the bores' inner radii are small enough

Figure 1a. Relevant AM design guidelines for remanufacturing [17]

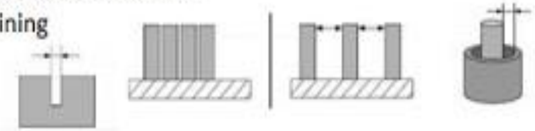
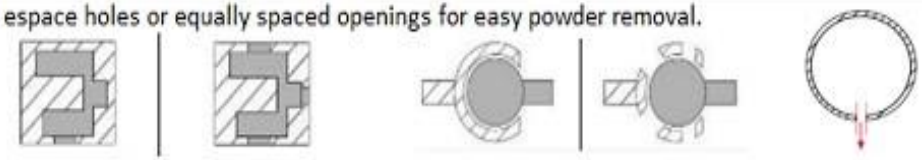
PRINCIPLE	EXPLANATION
Gaps between round features, vertical orientation and manfactured parts	Gaps below specifications may show large powder adhesion and merging of opposite gap areas Consider free space between manufactured parts in order to ease final machining 
Reduce Gap areas	Design gap areas as small as possible Reduction of powder adhesion 
Use cavities	Use cavities in order to reduce the part volume to be exposured. Also, the wt of part will be reduced Reduction of manufacturing time and cost. 
Multiple openings fo complex parts	They can be espace holes or equally spaced openings for easy powder removal. 
Remove material	Avoid material accumulation Reduction of part volume reduces manufacturing time, cost and wt of the part 
Offset supports	The most simple form of support is to fill in the area that needs support, and then cut this out when the build is complete by wire cutting or machining. If the support area is to be removed with wire cutting, a small hole needs to be placed in the support area to allow the wire to be located  Offset supports require less machining. They rise vertically and then angle in to support specific surfaces. The base of the support is usually removed with the wire cut removal of the part, requiring only the supported surface to be machined.
Avoid sharp corners	Design parts with minimum radii of approximately 0.5mm. Very sharp edges cannot be built in DMLS 

Figure 2b. Relevant AM design guidelines for remanufacturing [17]

3.1. DfAM tools-CAD phase

3.1.1. Topology optimization (TO)

Within a given design space and for a given boundary conditions, topology optimization, as a numerical methodology, optimizes the material layout such that the resulting layout encounters a prescribed set of performances [15]. Therefore, any material that is not accomplishing a useful function within a part will be removed.

Referring to Plocher and Panesar [18] who reviewed developments in the design and structural optimization (Figure 5) in additive manufacturing, topology optimization, a mathematically-driven technique, is defined by an automated process whereby a quantifiable target objective is optimized by an iterative numerical method. Topology optimization become a general practice in commercial software (Altair Optistruct, COMSOL, nTopology, solidThinking Inspire, etc.) to optimize the size or shape of the final component to reach the target objective. At the bosom of each structural TO problem resides an objective function that needs to be optimized (minimized or maximized) while being under a set of constraints; for instance volume, displacement, or frequency. In the case where light weighting is the objective, density would be the design variable in the TO iterative process following the steps of Finite Element Analysis (FEA), sensitivity analysis, regularizations, and optimization.

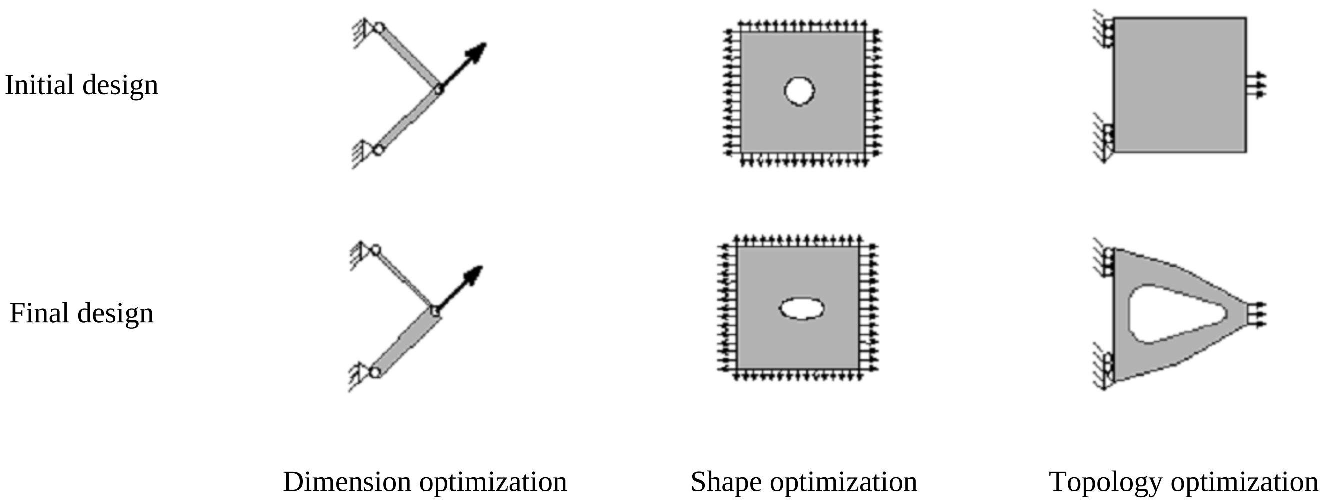


Figure 3. Different subclasses of optimization of structures [18]

Re-designing components for AM, mainly complex ones, has been considered by Priarone et al. [19] as the way to reach the objective of saving resources, either in used materials or energy consumption. Namely, topological optimization has been applied in this context to lightweight components [7], especially transportation system ones.

3.1.2. Lattice generation

AM enables the fabrication of highly complex geometries, such as 3D lattice structures (Figure 6). Lattices, three-dimensional periodic cellular structures, have been established in multiple engineering applications due to their high specific stiffness, strength, impact absorption properties, thermal isolation capability, and ability to replace support material [20]. A lattice is a chain of interconnected struts, analyzed as representative unit cells or volume elements tessellated in three dimensions. The unit cell encloses many basic lattice properties, such as strut diameter and lattice type. Lattice generation, an expertise-driven technique, constitutes a design practice that contributes to a light weighting strategy, and in exchange greatly compromises stiffness [18].

To help designers, some specialized software tools have been developed at both academic and professional levels. To give non-exclusive examples, K3DSurf (or MathMod) as the academic one, and Simpleware ScanIP, Selective Space Structure, Altair Optistruct, and Autodesk Within as commercial ones.

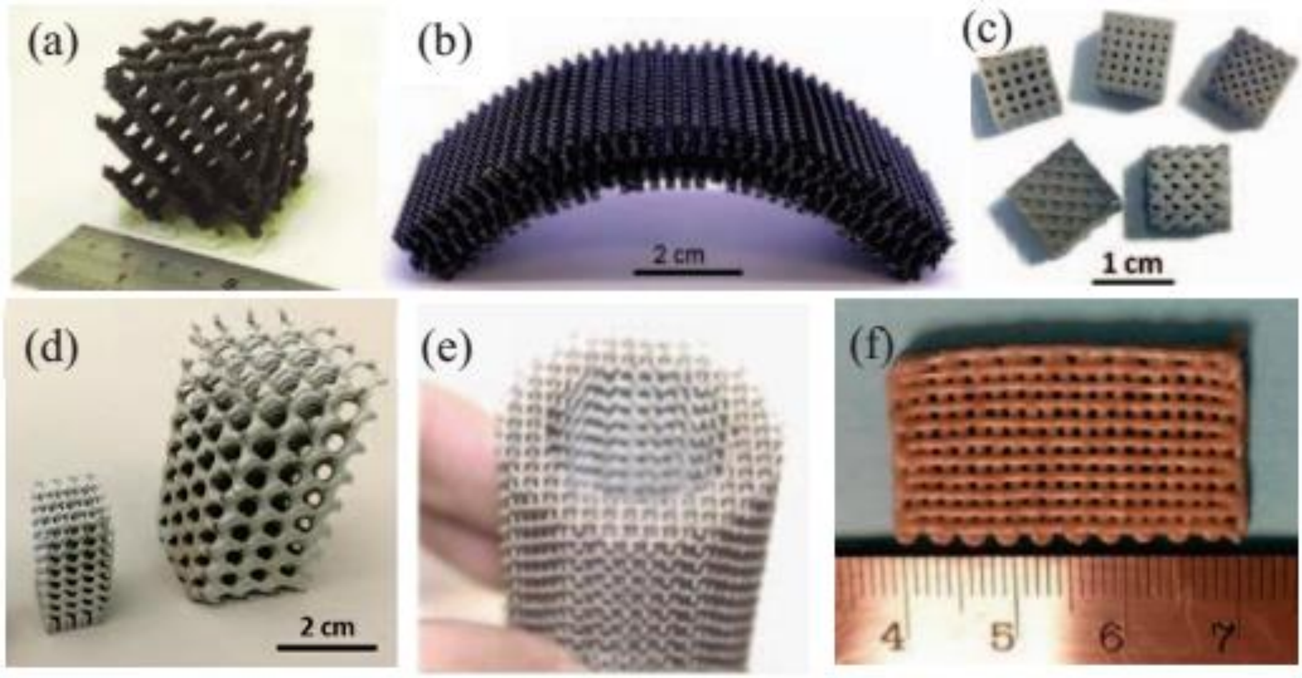


Figure 4. Lattice structures examples produced by different AM processes: (a) FDM, (b) SLA, (c) SLS, (d) SLM, (e) EBM, and (f) Freeze-form Extrusion Fabrication-FEF [21]

3.1.3. Generative design

Generative design formally combines lattice generation and topology optimization through a parallel implementation to offer a portfolio of solutions namely parts that are optimized for numerous objectives with conflicting constraints [18]. Altair Optistruct and Autodesk Within software integrate topology optimization into the lattice structure generation process.

Whether specifically dedicated to topological optimization or to lattice generation; or integrated into CAD software, this design software is very useful in the embodiment design stage. In the earlier conceptual stage, these tools should be foreseen to be used. More rudimentary tools, but very useful, are used in the conceptual phase such as the DfAM worksheet.

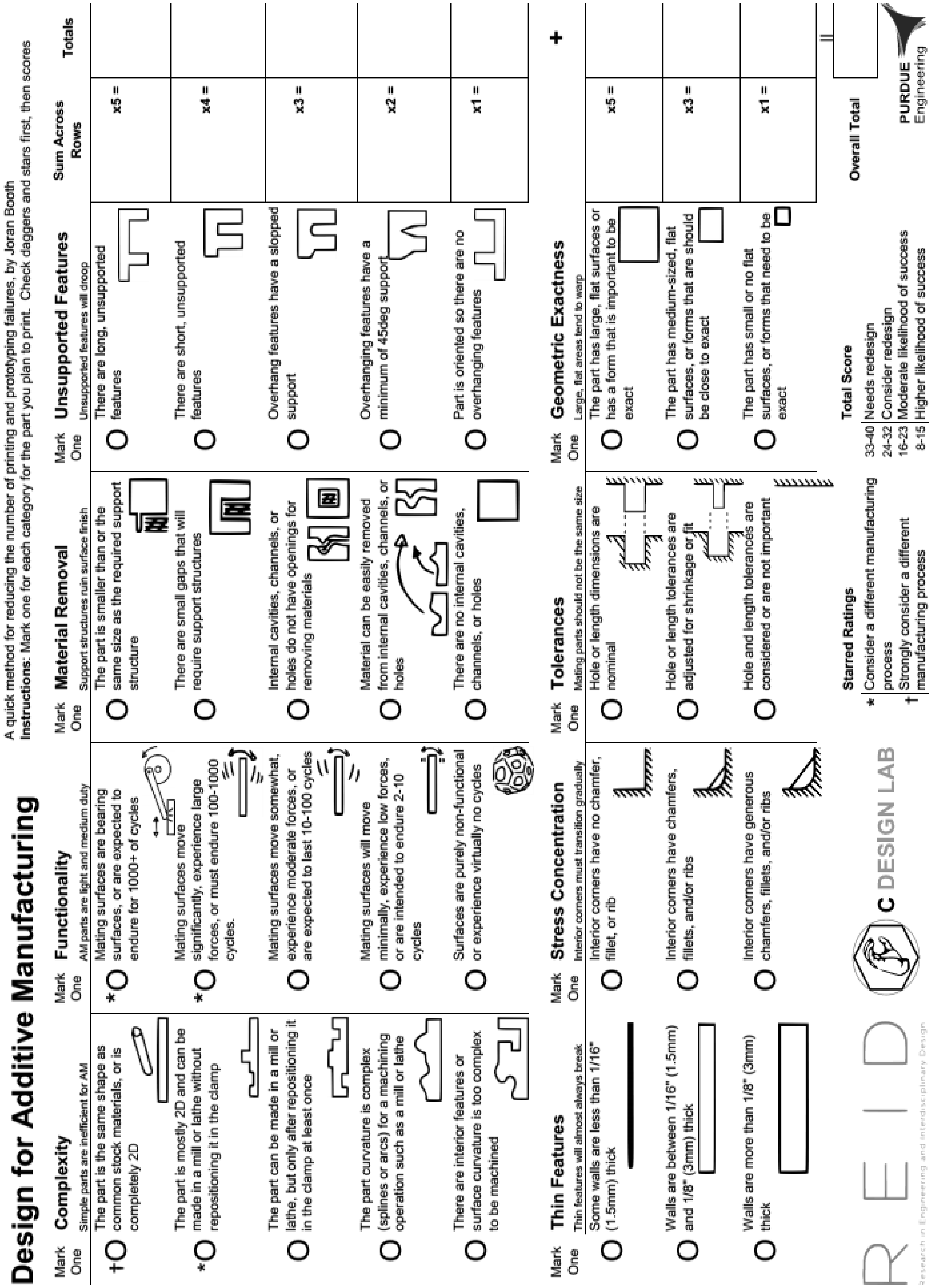
3.2. DfAM tools-EDS phase

3.2.1. LiDS wheel

In a context of a design for environment (DfE) approach, Markou et al. [22] introduced a methodology for conceptual design. The proposed methodology implementation is based on a creativity session where dedicated support, needed to guide the designer's choices in terms of environmental decisions, is provided. A Life-Cycle Design Strategies (LiDS) wheel adapted for additive manufacturing and a table containing a full description of the different AM processes are given to the users. AM processes information in terms of AM category, AM technology, material state (powder/liquid), material capability (metal/polymer), inert gas, energy consumption rate (ECR) (kWh/kg), post-processing method, and need of water has been used successfully to support eco-designing decisions in creativity sessions.

3.2.2. DfAM worksheet

Booth et al. [23] developed a DfAM worksheet designed for novices and intermittent users of AM technologies. This DfAM worksheet (Figure 7) could help designers assess the potential quality of an additive-manufactured part by giving intuitive feedback and indirectly advocating changes to enhance a design. The benefit of this DfAM worksheet is that it can help to streamline designs and decrease manufacturing errors.



Design for Additive Manufacturing

A quick method for reducing the number of printing and prototyping failures, by Joran Booth
Instructions: Mark one for each category for the part you plan to print. Check daggers and stars first, then scores

Mark One	Complexity Simple parts are inefficient for AM	Mark One	Functionality AM parts are light and medium duty	Mark One	Material Removal Support structures ruin surface finish	Mark One	Unsupported Features Unsupported features will droop	Sum Across Rows	Totals
†O	The part is the same shape as common stock materials, or is completely 2D	*O	Mating surfaces are bearing surfaces, or are expected to endure for 1000+ of cycles	O	The part is smaller than or the same size as the required support structure	O	There are long, unsupported features	x5 =	
*O	The part is mostly 2D and can be made in a mill or lathe without repositioning it in the clamp	*O	Mating surfaces move significantly, experience large forces, or must endure 100-1000 cycles.	O	There are small gaps that will require support structures	O	There are short, unsupported features	x4 =	
O	The part can be made in a mill or lathe, but only after repositioning it in the clamp at least once	O	Mating surfaces move somewhat, experience moderate forces, or are expected to last 10-100 cycles	O	Internal cavities, channels, or holes do not have openings for removing materials	O	Overhang features have a slopped support	x3 =	
O	The part curvature is complex (splines or arcs) for a machining operation such as a mill or lathe	O	Mating surfaces will move minimally, experience low forces, or are intended to endure 2-10 cycles	O	Material can be easily removed from internal cavities, channels, or holes	O	Overhanging features have a minimum of 45deg support	x2 =	
O	There are interior features or surface curvature is too complex to be machined	O	Surfaces are purely non-functional or experience virtually no cycles	O	There are no internal cavities, channels, or holes	O	Part is oriented so there are no overhanging features	x1 =	

Mark One	Thin Features Thin features will almost always break	Mark One	Stress Concentration Interior corners must transition gradually	Mark One	Tolerances Mating parts should not be the same size	Mark One	Geometric Exactness Large, flat areas tend to warp	Sum Across Rows	Totals +
O	Some walls are less than 1/16" (1.5mm) thick	O	Interior corners have no chamfer, fillet, or rib	O	Hole or length dimensions are nominal	O	The part has large, flat surfaces or has a form that is important to be exact	x5 =	
O	Walls are between 1/16" (1.5mm) and 1/8" (3mm) thick	O	Interior corners have chamfers, fillets, and/or ribs	O	Hole or length tolerances are adjusted for shrinkage or fit	O	The part has medium-sized, flat surfaces, or forms that are should be close to exact	x3 =	
O	Walls are more than 1/8" (3mm) thick	O	Interior corners have generous chamfers, fillets, and/or ribs	O	Hole and length tolerances are considered or are not important	O	The part has small or no flat surfaces, or forms that need to be exact	x1 =	

Overall Total =

Starred Ratings
- * Consider a different manufacturing process
- † Strongly consider a different manufacturing process

Total Score
- 33-40 Needs redesign
- 24-32 Consider redesign
- 16-23 Moderate likelihood of success
- 8-15 Higher likelihood of success

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Figure 5. Booth DfAM worksheet [23]

4. Results and discussion

The state of the art of DfAM rules, guidelines, best practices, and tools presented in the previous sections shows multiple and versatile knowledge that a designer for AM needs to be acquainted with in the different design process stages. The designer needs to be conscious not only of the AM opportunities but also of the AM design constraints. From the author's point of view, the early design stage is crucial as the required identification and the collected data in terms of specific DfAM rules and guidelines need to be explored in depth. The earlier the designers satisfy the DfAM rules and guidelines, the more efficient the design would be. Indeed, the iterative work needed in the creation of a design could be scaled down by acting preventively. A proposed framework that involves the different design tools presented earlier is shown in Figure 8.

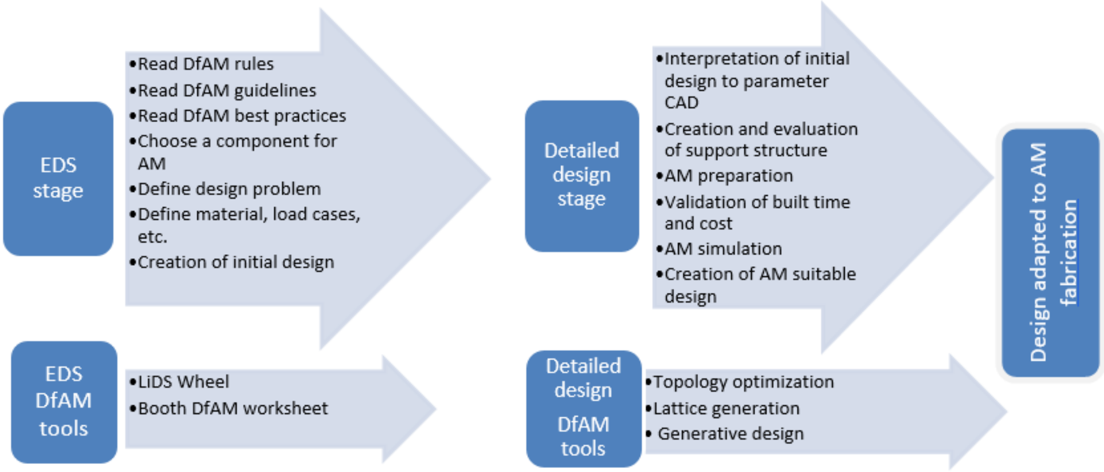

Figure 8. Proposed DfAM framework

5. Conclusions

AM offers exclusive fabrication capabilities that engineering designers have to know how to exploit. To enable this exploitation, it is essential to answer the question of what principles (rules and guidelines) can guide DfAM. Based on the review, the classification of available tools and methods according to the different stages of the design process is made. Furthermore, a new detailed DfAM framework has been proposed together with a mapping of available design support in the form of DfAM rules, guidelines, best practices, and tools. The framework shows the potential for reducing the iterative work within the design process as the designer is informed from the start of DfAM opportunities and constraints. Nonetheless, extensive validation of the proposed DfAM framework needs to be realized in future work.

Declaration of competing interest

The authors declare that they have any known financial or non-financial competing interests in any material discussed in this paper.

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