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Design for additive manufacturing: Framework and methodology

Tom Vaneker (2)[a,*], Alain Bernard (1)[b], Giovanni Moroni (2)[c], Ian Gibson[a], Yicha Zhang[d]

[a] Faculty of Engineering Technology, University of Twente, the Netherlands
[b] Ecole Centrale de Nantes, LS2N UMR CNRS 6004, France
[c] Department of Mechanical Engineering, Politecnico di Milano, Italy
[d] Université de Bourgogne Franche-Comté, Université de Technologie de Belfort-Montbéliard, ICB UMR CNRS 6303, France

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ABSTRACT

In recent decades additive manufacturing (AM) has evolved from a prototyping to a production technology. It is used to produce end-use-parts for medical, aerospace, automotive and other industrial applications from small series up to 100,000 of commercially successful products. Metal additive manufacturing processes are relatively slow, require complex preparation and post-processing treatment while using expensive machinery, resulting in high production costs per product. Design for Additive Manufacturing (DfAM) aims at optimizing the product design to deal with the complexity of the production processes, while also defining decisive benefits of the AM based product in the usage stages of its life cycle. Recent investigations have shown that the lack of knowledge on DfAM tools and techniques are seen as one of the barriers for the further implementation of AM. This paper presents a framework for DfAM methods and tools, subdivided into three distinct stages of product development: AM process selection, product redesign for functionality enhancement, and product optimization for the AM process chosen. It will illustrate the applicability of the design framework using examples from both research and industry.

1. Introduction

Additive manufacturing (AM) was first developed in the late 1980's [174] with increasing quality and market penetration ever since. Starting as prototyping technology it has developed into a technology that allows for mass production of end use parts [69]. In 2018 BMW has reported on 3D printing of its one millionth component in series production. Major AM markets [23] that include aerospace, automotive, consumer products, medical, and general industries report simular success stories. According to a study by Deloitte [46] AM is implemented within industry to increase the perceived value in any of three area's: profit, risk and time. Next to that the tactical path along which these industries have incorporated AM implementation can be characterized by product and/or supply chain change (see Table 1, Fig. 1). Four different paths have been identified:

- Path 1 describes companies that do not seek radical modification of their products and supply chain, but look at AM to improve their value proposition to the customer. Typical examples of the use of AM for path 1 are printed prototypes and tools and fixtures.
- Path 2 looks at AM as a means to define new business cases in which the production of end user products can be realized beneficially. Examples include for example the production of spare parts and production on problematic production locations like space [72], war zones [35] and the oil&gas industry [67].
- Path 3 describes strategies being enabled by AM based new product performance. Examples are the fuel nozzle by GE [116], embedded electronics [28] and lightweight structures.
- Path 4 describes companies that base their new business models on changes in both the supply chains and the products. An example for this path is the 3D scanning and printing of custom shoes in retail stores [55].

All tactical development paths described above deal with product design within an AM-based supply chain. It is required both for the realization of AM-based enhanced product performance as well as when printing more standard product designs; these designs also

Table 1
Repeatedly used abbreviations.

AM	Additive manufacturing
DED	Directed Energy Deposition
DfAM	Design for Additive Manufacturing
DfMA	Design for Manufacturing and Assembly
DfX	Design for X
E-PBF	Electronbeam Powder Bed Fusion
FDA	Federal Food and Drug Administration
FGM	Functionally Graded Materials
GD	Generative Design
GD&T	Geometric Dimensioning and Tolerancing.
GPS	Geometrical Product Specification
L-PBF	Laser-Powder Bed Fusion
STL	Standard Tessellation Language
TO	Topology Optimization

* Corresponding author.
E-mail address: t.vaneker@utwente.nl (T. Vaneker).

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Fig. 1. Framework for understanding AM paths and value [46].

have to be optimized for specific AM process opportunities and constraints so they are produced reliably, on time and cost efficiently. Design for Additive Manufacturing (DfAM) describes methodologies used to optimize the product design with the goal of improving performance in all lifecycle stages.

The lack of (structured) knowledge on DfAM has been identified as one of the barriers that holds back further adoption of AM in industry [39,161,183]. This can be attributed to the attention given to AM as a production technology, which only blossomed over the last decade. Attention to design for AM trailed behind and only grew in importance when interest in commercial production of end user goods increased. Further reasons for the lack of structured knowledge is that AM is not a single production method but an umbrella term for many production methods, all with their own benefits and drawbacks. Finally, it has been shown that education on AM and DfAM needs more attention, both at applied and university level, see for example [139].

The CIRP community has published papers related to AM processes [56,80,96–98,108,147], AM materials [27], specific AM application areas [17,95] and AM geometrical aspects [105]. The CIRP keynote paper by Thompson et al. [162] focused on DfAM and disclosed the width and complexity of the DfAM theme, and addressed many of the themes that should be considered as part of product development for AM. These topics ranged from design strategies and artefact design up to economic and strategic considerations on the implementation of (design for) AM within industrial product development processes. The paper focussed on design considerations that should be addressed when deciding on the transition from classical production processes to additive manufacturing. This keynote paper focuses on the state of the art on methods and tools related to the design of geometry or functional AM artefacts within an industrial setting. Methods and tools, and the way they are presented, will focus on the needs of AM product designers. A general introduction to AM processes and process steps will be presented in Section 2. Section 3 will present a framework for the selection and application of DfAM methods and tools. In Sections 4–8, the DfAM framework will be discussed in more detail; lightweighting, internal topology, surface topolgy, material complexity and part integration. Finally Section 9 will discuss future DfAM related challenges. When required, methods and examples of application will focus on AM based production of metal parts in an industrial setting. The applicability of the design framework is however not limited to the examples given but can, at a generic level, be apllied to the majority of the known AM processes.

2. Additive manufacturing

AM is defined by the ISO/ASTM joint standard 52900:2018 [82] as the process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies. Note that this definition is very general and can be applied to a wide range of technologies. Although many of us have a common image of what an AM machine looks like, it is clear for instance that there is no restriction on how many materials we may join together or that we need to join them in layers. Hybrid technologies that for example use additive plus subtractive processes within a single machine may therefore not be considered as AM machines in the strict definition of the term. For the near future it is foreseen that fully automated manufacturing lines, combining AM in tight and repetitive sequences alongside other fully automated production and handling processes, will become the standard for the modern factory.

2.1. AM processes

According to ISO/ASTM [82] there are currently seven AM process categories that result in a 3D CAD model being formed into a solid, integrated part:

- Binder jetting: droplet printing of a liquid used to bind powder particles together;
- Directed energy deposition: material is simultaneously fed into a moving focused energy region;
- Material extrusion: material is fed through a nozzle in a liquid state after which solidifies;
- Material jetting: material is jetted in liquid droplet form after which it solidifies;
- Powder bed fusion: powder material is selectively heated so that the particles partially or fully melt to form a solid matrix;
- Sheet lamination: sheets of material are bonded together either before or after the part outline is separated from the sheets;
- Vat photopolymerisation: a platform is dropped through or raised above a vat of liquid resin where light is used to selectively solidify it.

Most of these categories have so far resulted mainly in machines that are designed for one-off prototypes or for production that heavily employs manual work. Whilst the AM technology itself is largely automated, the design process, machine setup and finishing stages may require a significant amount of knowledge and skills to perform. Furthermore, many of these activities are quite experimental and iterative in nature.

All the above processes were initially developed to create parts from different polymeric materials, with the exception of sheet lamination (paper). Some of these technologies have now been developed to a level where they have been incorporated into large batch production. Some of these batches can be considered to be part of a continuous production line. The most well-known of these would be AM machines used in production of teeth aligners [82] and hearing aids [159]. These examples show that when the additional complexity of form and/or the individual part cost allows it, AM can be used for final part production of (polymer) parts.

The impact of AM on process chain towards final production is however most heavily felt when producing metal parts. All of the above process categories have a means in which to arrive at a metal part. There are in general four ways in which this can be achieved.

The first approach is by mixing metal particles with the material joining mechanism. For example, metal particles can be added to photopolymers in vat photopolymerisation or mixed with polymer powder in powder bed fusion or with filament in material extrusion. In general this will end in a blended part that exhibits some of the properties of the metal like improved surface hardness or heat deflection.

The second approach is where the parts above are used in a secondary furnace cycle to burn off the polymer and cause the metal

particles to sinter together. This process therefore requires an additional programmable furnace to achieve this effect. In addition to the process categories mentioned in the previous paragraph, binder jetting is also widely used in this manner. In fact, this process can achieve very acceptable results. It should be noted in particular that part shrinkage will occur using this approach. This shrinkage can be minimised if an infiltrant is used to fill in voids prior to densification. For example 420 stainless steel parts can be infiltrated with bronze at 1100 °C [58]. Many technologies have been refined to a level where geometric tolerances are highly predictable and achieving up to 97% final density values.

Conventional polymer AM materials can often be used in casting processes to achieve metal parts. Some of the original processes were developed around waxes as a means to integrate with conventional investment casting. It was found later that other, stronger polymers could be used in this way provided the casting shells were strengthened and the burnout conditions were modified.

Four of the above process categories can directly produce metal parts; powder bed fusion, directed energy deposition, material jetting, and sheet lamination. It is interesting to note that sheet lamination is largely a hybrid process. In sheet lamination there can be a large amount of material, often much more than is used for the part itself, that is separated from the part in a subtractive manner during the AM process. These sheets can be metal and bonded together using ultrasonic bonding. This is a low temperature welding process for joining dissimular metals and can for example allow embedding of electronics in the structure without damaging it [29]. It is a niche AM route towards metal parts.

By far the most widely used AM approach for metal parts is powder bed fusion. This is largely because of the basic simplicity of the process combined with the fact that a range metals is readily available and suitable for mainstream applications. A beam of energy is used to selectively melt the powders to form the solid part. Electron beam melting is available but most systems use laser energy, normally in a sealed chamber, in an inert gas environment or a vacuum. This sealed chamber may be at an elevated temperature but still considerably below the melting point of the metal. Since this means very large thermal gradients, it is normal to connect the parts to a solid substrate in a similar way to processes that require support structures. These supports have a different purpose in that they anchor the part to prevent internal stress warpage during build.

Directed energy deposition is a process that almost entirely focuses on metal parts. A high energy source is used to melt metals that are delivered in either powder or wire form. The energy focal point is also where the material is delivered and so there is a periodic melting followed by rapid solidification. Similar issues to powder bed fusion exist regarding residual stresses with the additional complexity of a significantly varying thermal environment. Since there is no surrounding powder to help stabilise the heat transfer, the directed energy deposition process will have differing cooling profiles dependent on the mass of surrounding material at the energy delivery point.

Material jetting for the production of metal parts is hampered by the high temperatures needed to get the metals in the proper liquid state. As a result this technology, when used to directly fabricate metal parts, is still in the development stage.

2.2. AM process steps

The process of creating an additively manufactured product can be subdevided into seven steps.

1 ***Model design.*** 3D CAD software can be used to create a solid or surface model or (medical) scan data is used to create the 3D geometry;
2 ***STL file creation.*** The 3D model is converted into a file format that is understood by AM machines. The STL file format is widely used and approximates the 3D model by a surface that is constructed using triangles. Other file formats exist that are better suited to advanced AM features like multi material parts [75];
3 ***Build preperation.*** The STL file is transferred to the build preparation software, where the location(s) and orientation of the part(s) in the build envelope are defined. The software slices the geometry into individual layers. For each layer the geometric data of that layer, in combination with the machine parameters, like laser power, layer thickness and scan patterns, is translated into build instructions for the AM machine;
4 ***The build process.*** The build process itself takes place (depending on the actual product and process; hours to days), is executed autonomously and only requires occasional supervision;
5 ***Part removal and post-processing***. After the build process the part is removed from the build plate/envelope and excess material (powder, support structures) is removed. Additional post-processing steps might be needed to improve the functional characteristics of the part.
6 ***Quality and inspection***. Often quality and inspection methods are applied that are based on other production technologies like casting and forging. But the complexity of the geometry can induce unique inspection problems like inaccesable surfaces or the absence of measuring datum planes [173];
7 ***Application.*** For most industrial parts produced by additive manufacturing the expected benefits in the use phase are the reason for designing parts to be created by additive manufacturing.

2.3. AM design stages

As mentioned in Thompson et al. [162], the AM design process has to take into account a lot of aspects related to several key performance indicators. Globally, as defined in the standard ISO/ASTM 52910:2018 [82] the AM design steps can be structured into three global stages.

The first stage relates to go/no-go evaluations concerning the part, tool or product to be considered. The main question is “is AM adapted to this object or set of objects with respect to its/their requirements?”. Basically, the first challenge at this stage is to find a technology, and more over a value chain that is candidate for the production of this/these objects. Manufacturability issues will have to be checked at this stage even before defining any geometry.

The second stage applies all the rules and constraints defined by the requirements, taking into account several aspects (topological optimization, material, mechanical properties, etc.). Before that, however, crucial decisions must be made with respect to functional decomposition and functional integration. This initial decision implies the necessary set of parts and initiates the definition of individual objects in the system. Even for a unique part, it is necessary to go through this functional decomposition phase, mostly based on features in this case. One later decision will be to define the complete manufacturing for each feature as well as the scheduling of the individual manufacturing operations, with possible use of different manufacturing technologies. The material and its characteristics will also have to be defined for each voxel of the part. The definition of the material characteristics (type, density, etc.) must be fixed as well as the definition of transitions between different materials in different regions of the objects. These possibilities are limited to AM technologies that allow assembly of different materials or grading material characteristics in a given part. Simulation tools are currently not sufficiently mature to assist designers for this purpose.

The third stage corresponds to the final check and optimization of process characteristics with respect to the best possible properties of the manufactured objects. For example, the number of parts produced is dependent on the choice of orientation of the part and consequently on the support structures that are minimized with respect to an optimum part geometry.

These three global design stages serve to minimize the technical and economic risks before going to manufacturing. Design does not therefore just rely on a simple set of design guidelines. This is much more complicated and DfAM is in fact “Design for an AM-based value chain” including post-processes and quality control. A global and

systemic vision of the complete value chain has to be considered with respect to global indicators like in particular lead time, cost and quality, in order to evaluate feasibility, suitability and stability of AM-based value chain performances [114].

3. A DfAM framework

Design for manufacturing and assembly [25] has been around for many years and deals with the design of products while focussing on both the manufacturing and assembly process. The goal of DfMA is to include manufacturing and assembly knowledge early in the design proces to increase chances of success and shorten the development cycle [22]. Many variants exist, focussed for example on specific production technologies like injection molding or casting. DfAM focusses on AM processes but differs from other DfX processes. It deals with many different AM process variants and needs to take the whole process chain into account to be successful while research has shown that the number of interacting aspects that define successful production is large [147]. Finally, AM is a new group of processes that provides other opportunities and constraints to traditional forming and subtractive processes which implies non-traditional approaches to product design are required.

Many papers exist on individual aspects of the design process while for a succesful design process all relevant aspects should be taken into account. A framework (Fig. 2) that links many DfAM aspects together has been developed, based on that presented in [83] and compiled based on the insights of the authors. The framework defines a structured method to link design challenges to specific design goals and focusses on the 3 stages presented in Section 2.3. In the next chapters and sections these stages will be discussed in more detail. Examples used will focus on AM-based manufacturing of metal products although the framework is generic in nature and can also be applied for other material/process combinations.

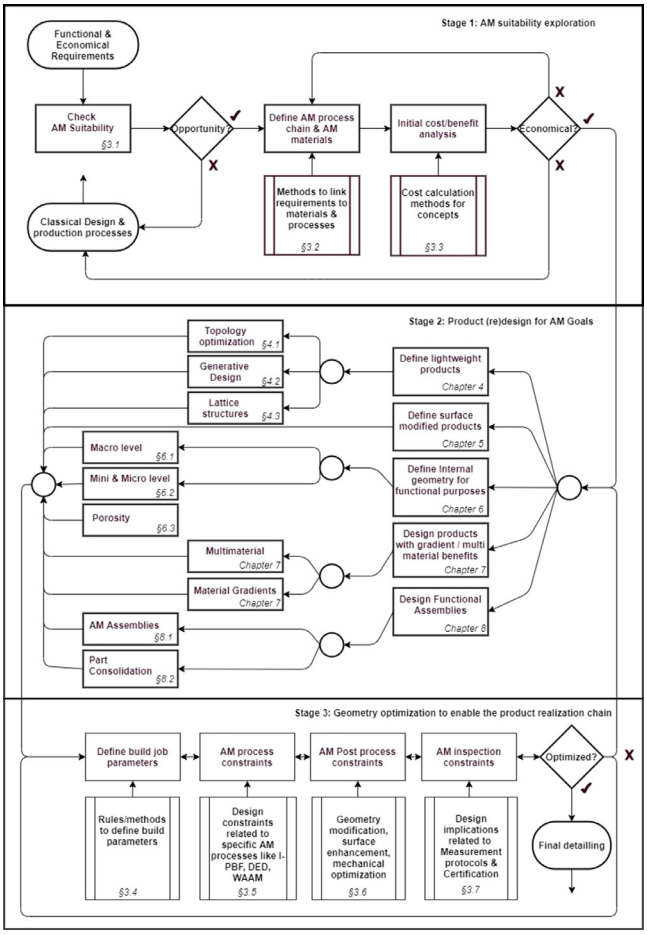

Fig. 2. Design framework linking DfAM stages, actions and goals.

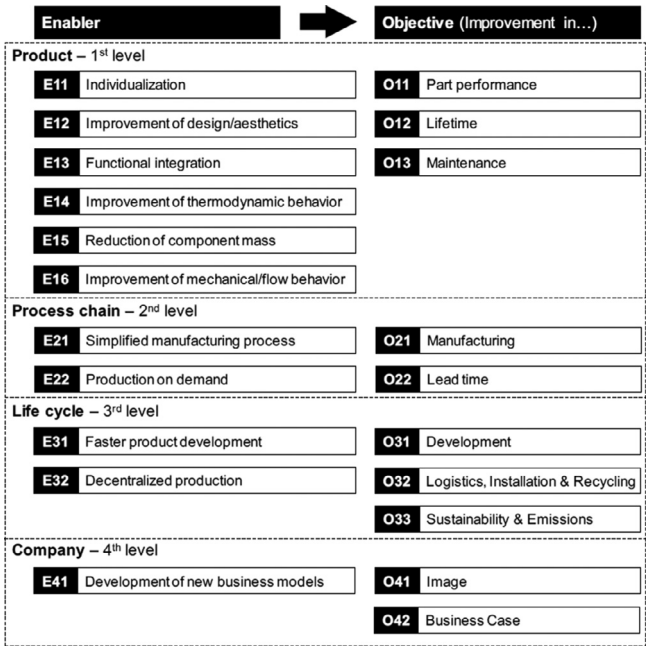

Fig. 3. Enablers and objectives for early identification of AM applicability [149].

3.1. AM suitability

Additive manufacturing is a relatively new group of production processes, of which integration in industry is just starting to gain momentum. This momentum might be attributed to the claims of a future where AM will realize low cost efficient production of any shape in any material [113]. Current industrial additive manufacturing practice shows that this bright future is yet to be [149]. Timely identification of the match between design task, product requirements and AM capabilities is needed.

[83] proposes to base this evaluation on the following criteria:

- Do available AM materials match the product application?
- Does the product design fit the build envelope of AM hardware?
- Can the product functionality improve when applying the following product design modifications or product opportunities?

- Part customization
- Lightweighting
- Use of internal channels or structures
- Functional integration
- The use of designed surface structures
- The use of multi-material or gradient material parts.

[149] takes a more holistic view and recognizes four implementation levels, ten product objectives and eleven AM enablers to obtain those objectives (see Fig. 3). For example [10,24] propose to also add concept based economic considerations, both at the functional and the manufacturing levels. This is to evaluate the balance between the expected economic benefits of product design opportunities against, in most cases, the increased manufacturing costs. Finally [24] proposes to add the sustainability objective, although [113] showed that this objective is of relative low importance in industry (less than 1% of use cases investigated). The dominant objectives established in that last paper are improved part performance (65.6%), manufacturing (57.8%) and reduction of lead time (29.7%).

3.2. AM material, process and machine selection

If AM potential has been established then AM resources should be identified, as these affect downstream design choices. This includes the decision between direct AM-based production, indirect AM-based production (printing of dies, moulds, tools etc.) or hybrid

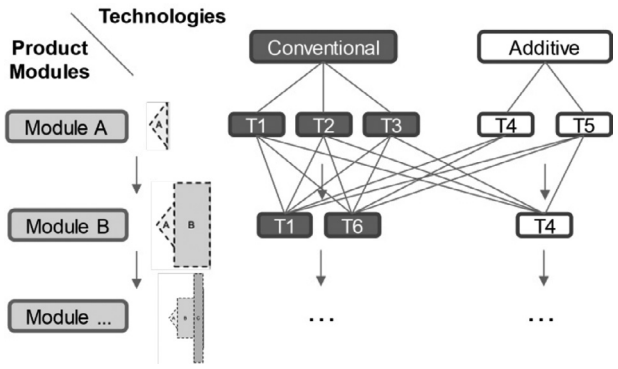

Fig. 4. Process chain selection [86].

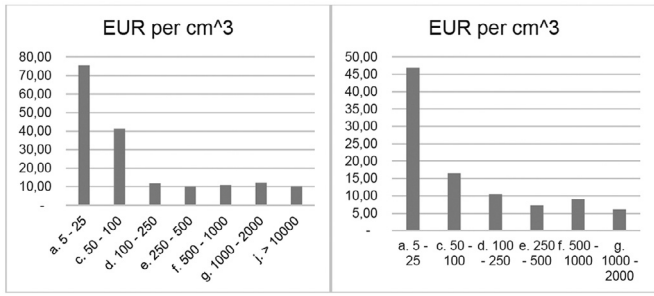

Fig. 5. Cost price per cm^3 in a buy scenario, depending on total order volume. Stainless steel (left), Aluminium (Right) [15].

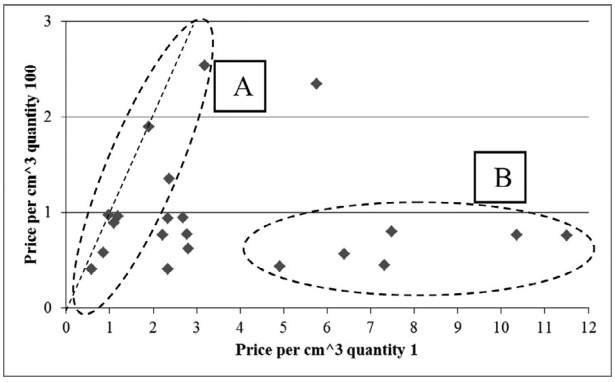

Fig. 6. Effect of order quantity on production price per cm^3. Values displayed for PA12. [15].

approaches. Also post-processing steps, needed to reach the required product characteristics, could be identified in this stage. For reasons of process chain selection, hybrid production processes can be subdivided based on the method used to generate the bulk of the geometry. From an industrial perspective some hybrid technologies use conventional technologies to create the bulk of the part and use AM as a subsequent production method to add detailing features. This sequencing of processes can have economic benefits or can result in parts that exceed the standard build chamber dimensions. An AM process that produces the bulk of the part using AM technologies and integrates subtractive technologies during the build process can be seen as the second group of hybrid processes. For metal parts this sub-group typically consists of DED-based metal additive manufacturing technologies and with milling to post-process functional, internal or hard to reach surfaces.

Jacob [86] (Fig. 4) subdivides parts into modules where, for each module, different conventional and additive production technologies are available. Based on interdependencies and sequencing of process steps, alternative processing chains can be generated and evaluated. Based on the design requirements and selections already made (e.g. material type), Bikas [24] proposes to use screening and selection for AM processes based on criteria related to machine, material, process and part constraints. This method however ignores hybrid production technologies and remains unclear on the details of the constraints used. The Senvol database [150] links AM processes to available materials and build envelops of industrial AM machines. Also the (software supported) screening and ranking method proposed by Ashby can be applied for AM material and process selection [9,166].

3.3. Initial cost estimation

The decision to apply additive manufacturing for functional parts involves balancing the cost of additive manufacturing against the expected benefits during the design, production and use phase. Although the cost/benefits analysis during the early design stage is important, information required for detailed cost estimation is often missing. Knowledge on the expected product volume, production technology and required post-processing steps can give insight into the expected costs. For the early cost estimation of the production of the part, the costs are often expressed as cost per cm^3 of the printed part. Most cost estimations found in literature only take the process related post-processing steps (e.g. support removal) into consideration and additional costs must be taken into account when the functionality (dimensions, tolerances, mechanical properties etc.) of the printed part has to be improved also.

Most cost estimation calculations are based on the assumption of in-house production and an idealized representation of the AM process investigated. It is assumed that one AM machine is used for one product the whole life time of the machine, resulting in a high machine load (%). For example, Baumers [18] presents a cost breakdown for metal powder bed based production of a stainless steel 304L product with wire erosion support removal and de-powdering as post processing steps. Based on that analysis four major cost aspects were identified: Indirect cost (machine cost, wire erosion costs etc), material costs, labor costs, and risk associated costs. Risk related costs include build failures and accounts for 26% of the AM unit cost. Based on 5000 production hours per year, and an average of nineteen production hours per workable day, a cost of €8.25 / cm^3 of the printed product was found. In [19] the production of laser based powder bed fusion (L-PBF) system was compared to an electron beam variant (E-PBF). The AM deposition rates are relatively slow (L-PBF 37.58 g/h, E-PBF 69.24 g/h) and are identified as the major driver for the manufacturing costs.

An alternative cost estimation study was presented by Baldinger [15] and focusses on buy scenarios for AM parts. The cost estimations are based on reviews of the cost price for obtaining an AM part through commercial service providers and focused on both plastic (PA12) and metallic parts (stainless steel and aluminum). This research compared twenty-one AM service providers worldwide and found that the main cost drivers for this scenario are total volume of the order, packing density in the build envelope and the number of parts ordered. For small orders (total volume below 25 cm^3) the cost price per cm^3 is highest, while cost drops considerably for higher volume orders (>100 cm^3) and then ends-up in the range of the make scenario's (see Fig. 5).

The effect of number of parts ordered was also investigated (See Fig. 6). It seems that two strategies are applied by the companies; group A and B. Companies in group A use cost estimation strategies where part cost is almost independent of the number of parts ordered. These companies focus on optimizing the utilization of the build volume and have a slightly longer lead time (6.88 days). Companies in group B estimate cost for each order separately, have a large difference in cost per cm^3 for order sizes one and one-hundred, but have a slightly shorter lead time. Furthermore, estimations may vary significantly between service providers; a factor of 28 was found between the cheapest and the most expensive quotation for the same artefact. Table 2

Post-processing can add considerably to the cost of AM parts. Proper analysis on the cost of all post processing steps, until the functional part is realized, are scarce, as these functional requirements depend on specific use cases. In many cost models only the costs of

Table 2
Cost price per cm^3 for different materials and processes, based on the assumption of an optimal utilization of the build envelope and in house production. Sources used can be found in the table. The values presented are indicative only, as the calculation method and constants used have a large impact on the price per cm^3 presented.

Process	Material	Post Proc.	€/cm[c]	**Source**
L-PBF	SS 304L	WE, SR, PR	8.25[a]	[18]
	17-4 PH	WE, SR, PR	6.62–8.63	[21]
	17-4 PH	WE	7.17	[19]
	316L	WE	7.03	[20]
	AlSi10Mg	HT	7.97	[11],[b]
	Titanium	Undefined[c]	5.68	[53]
E-PBF	Ti-6Al-4V	None	2.77	[19]
	Titanium	Undefined	4.54	[53]
DED – powder	Titanium	Undefined	2.11	[53]
DED - wire	Titanium	Undefined	2.11	[53]
Binder Jetting	Titanium	Undefined	1.96	[53]

[a] Conversion rate £ to € 1.16. Conversion rate $ to € 0.90. Used for all entries in this column (if applicable).
[b] Assuming a density of 2.68 g/cm^3 and not 2.68 g/mm^3 as stated in the [11].
[c] In this research 10% was added to the cost price per cm^3 to account for post processing costs.

Table 3
Cost of post-processing operations [153].

Technique	Improvement goal	Cost indication
Stress relieve	Reduction/removal of thermal residual stresses	$500–600 per build plate
Part Removal	Remove part from the build plate – w-EDM	$200-300 per build plate
	Remove part from the build plate - Band saw	Low cost
Heat treatment	To improve microstructure & mechanical properties	$500 to $2,000 per batch
Hot isostatic pressing	To reduce porosity and improves fatigue live	$500 to $2,000 per batch
Machining	To improve accuracy of mating interfaces and surfaces. To add threads and remove supports.	Cost depends on geometry & material and fixture needs.
Surface treatments	Improve surface finish/ quality/surface roughness	$200 to $2,000 per batch
Inspection & Testing	Process qualification and part validation & certification	10–20% of total cost per part [148]

the post-processing steps directly related to the AM process are considered (for example de-powdering and support removal). The reasons that post-processing steps have a larger effect on the cost are their labor intensity. For example, Lindeman [112] calculated the post-processing costs (de-powdering, heat treatment and support removal) for metal parts produced by L-PBF to be between 4 and 14%. Simpson [153] gives a more generic overview of post-processing cost for metal AM (see Table 3).

3.4. Build job considerations

Build jobs are usually considered during the phase of process planning. Process planning is one of the most important activities in manufacturing planning and is a pivotal link between design and manufacturing. It deals with the selection of manufacturing operations and determination of their sequences based on economic and competitive criteria [178]. Compared to traditional processing, the context changes for Additive Manufacturing, but it is still within the manufacturing scope.

Although AM machines are highly integrated and automatic, before enabling the building process for a machine, there are also some preparation tasks that should be done after receiving a design model and its related production requirements. These tasks are tightly connected with the processing chain of AM. In this chain, optimization of the number of parts and their relative positioning in 2D (nesting) or in 3D (packing), is required when building multiple parts [194,195,198,199]. Support generation (when necessary) could be achieved before or after the nesting stage. Layer building can then be normally achieved by slicing the 3D set of nested or packed parts with their support structures. In some cases this stage is very different because the orientation of the part during the process changes (in DED for example). In such cases, the generation of the material deposition trajectory has to be achieved by taking into account non-planar layers. Alternative operations of adding and subtracting material and functions are sometimes considered to improve manufacturing efficiency, as an alternative solution to conventional methods like welding and machining. This approach, usually named hybrid manufacturing, needs specific AM process planning solutions in order to process from feature decomposition to a complete part recomposition, taking into account sequencing aspects and material excess regions for machining depending on expected dimensional and surface qualities.

However, orientation and placement have to be validated with respect to global thermal conditions of manufacturing. As material and geometry are obtained at the same time, it is mandatory to validate the material quality induced by the input of energy during the material transformation and the consequences on the metallurgical properties of the part. Consequently, potential deformations are also calculated and some modifications of strategy are also possible in order to compromise between production performance parameters and part material properties. Some simulation tools exist starting from the nested or packed global model integrating support structures. Progress is necessary in order to handle some particular difficulties related to the size of models, especially with lattice structures.

For some specific applications, process planning for AM may also generate assembly instructions. This occurs when a part's size exceeds the build volume of a machine and it can be decomposed into several small sections to be made separately.

3.5. AM process constraints

Like with all technologies, there are many constraints to AM. This section will focus on four primary constraints that are common to all AM process categories and particularly relevant to the AM of metals: Speed of build, materials, build envelope, and accuracy.

Although AM used to be called Rapid Prototyping, one is now quite accustomed to having prototypes built quickly, but this is difficult to scale up. Furthermore, there is increasing demand for AM to be used in mainstream production, which requires much faster throughput. AM has the benefits of geometric freedom, no minimum batch constraint and rapid change between batches, which meets many of the demands of modern manufacturing industry. The hunt is therefore on for faster AM technology.

Many metal AM systems use lasers due to the demand for large amounts of focussed energy. The ideal situation would be to provide the required energy over an entire layer simultaneously but so far this has not been demonstrated to be possible. A compromise is the supply of multiple laser beams controlled simultaneously [59]. Different lasers can be used to process different regions with finer spots being used for more detailed parts and wider beams to process bulk regions. Careful attention must be given to beam control so that they don't affect each other, including the vapour trails from the molten metal regions. A contrasting approach to increasing throughput for batch production of metal parts is the use of binder jetting methods [169] or material extrusion with metal-filled binder materials [51]. Such methods can achieve faster AM throughput and can be more easily scaled to create larger parts. The downsides relate to increases in post-processing times during heat treatment and during machine finishing, if required. These requirements are also driving the development of open-architecture, robot-based metal AM systems, like Wire Arc AM (WAAM) and Laser Metal Deposition (LMD).

There is a huge and increasing number of metals and other materials used to make products. Most of these metals are carefully chosen to suit product requirements in strength, chemical resistance,

thermal properties, processability, cost, etc. In comparison, there are a very few materials available in AM. There are a number of reasons for this. All AM processes are suited to a subset of materials, the requirements for which can be very specific, like the need for photocurable resins. Many materials can be formed by AM using thermal energy, but the amounts of energy vary considerably. It is not easy to melt metals in an AM process chamber specifically built for polymers for example. In addition, raw materials often need to be presented with well-defined morphology, like in filament or carefully-graded powder distributions.

However, even within a smaller range of materials the processing requirements can still be difficult to specify. Metals within L-PBF systems for example will absorb laser energy in different proportions. The physics around phase change behaviour and effects in the molten state can all be quite different, significantly affecting the final material microstructure. Furthermore, much of this is significantly different from other manufacturing processes like casting and forging. All these need to be carefully studied before AM materials can be released to the market. As, AM becomes more widespread, one can expect more materials to become available but it is widely accepted that range of materials needs to be increased. Having said that, current AM materials like Ti-6Al-4V, 316 stainless steel and CoCr alloys, etc. are all very popular and useful for many industrial applications.

Many products are made from metals because of the needs for strength and accuracy. In AM, part strength is often acceptable but part accuracy is very often not. Metal parts are often mated with others and so the joining surfaces must align with each other. Most metal AM processes create parts with poor surface finish, usually no better than 15 μm R_z and very often considerably worse. Machine finishing is therefore a common requirement as a post-process. This itself may present problems through difficulty in determining reference and registration points. Thermally induced distortion due to large temperature gradients during builds and corresponding residual stresses is also a common phenomenon for metal AM. Features may therefore be imprecisely located and it may be better to provide a machining allowance in the initial AM part design. The introduction of hybrid machines [103] that combine AM with subtractive and other manufacturing processes that operate in a sequential manner aim to overcome issues around part accuracy. This is particularly useful where the requirement is internal to the part geometry and difficult to achieve as a post-process.

3.6. AM post-processing constraints

For much of the time that AM technology has been under development, post-processing has been something that you would rather not do and eliminate if possible. Although this is logical, the emphasis has changed into something that you need to endure and therefore plan for, specifically if you are considering use in industry. AM is now considered as something that can shorten process chains, not eliminate them entirely. With that in mind this may also change the way to think about designing products. Sometimes it may be appropriate to include a design feature in the post-process rather than in the AM build itself.

Post-processing tasks can be broadly divided in terms of those that can require significant manual intervention and those that can be carried out in a largely automated fashion. Of course this depends on the available technology to achieve these tasks as well as the level of investment, quality issues, volume of production, etc.

Post-processing can also be considered in terms of those that need to be carried out due to the characteristics of the AM process used and those that are more aimed at enhancement of the AM parts. Like with the previous classification, there are overlaps or grey areas, around where exactly surface finish fits for example. This can also form part of the decision making in the process design

The AM technology specific processes mainly refer to the chosen build process and are aimed at providing a consistent quality of output suited to the general application. Many processes use support structures which have to be removed somehow, often requiring further finishing of regions where the supports connected with the part. Build strategies often revolve around minimising the amount of supports or avoiding key surfaces for aesthetic or accuracy reasons. For many machines, flat and curved surfaces can appear different due to the stair-stepping phenomena. Abrasive or chemical finishing can be used to make these surfaces appear more uniform. A further post-processing task can revolve around excess material that may be adhering to the part surfaces. This may be a surrounding material that protects these surfaces or they may be residual material due to inconsistencies in the process, similar to flash in moulding operations. Although specific to powder-based AM technology, pore-filling and densification can also be application specific in terms of the material chosen to create a fully dense part. Densification can also be in the form of a furnace cycle, perhaps using hot isostatic pressing (HIP). Since some processes can be slightly heterogeneous in nature, accounting for shrinkage may require careful preparation and difficult to precisely control.

Metal AM parts in particular are commonly used as fully functional parts. Choice of metal as a part material often relates to part strength and while precision can represent a problem. Finish machining of key surfaces is often required, much in the same way as we would treat a casting. In these specific regions it may be appropriate to grow some of these surfaces in the design phase to provide sufficient machining allowance to ensure high quality, accurate results. It can be argued that there will be fewer of these surfaces to finish since it is common thinking that AM allows for part consolidation due to the ability to create internalised features.

Although it is quite possible to print features like holes and screw-threads using AM, the precision demands on such features can be very stringent and beyond the capacity of the AM technology used. It may be possible to save material by printing a hole but the time taken to finish a partially-made hole may be the same, or even longer, than to drill a complete hole in a blank space. This may be even more relevant if the hole contained a screw thread. Again, it can be argued that this adds complexity to the process decision-making, but it is pertinent when relating to heavily industrial applications.

Coatings can go from simple paint jobs to improve aesthetics and seal against corrosive atmospheres through to providing significant functional properties, including bioactive features. Often, coatings are applied using a series of steps, requiring significant atmospheric management and control. These tasks may require significantly specialised facilities to those used in other production steps and as such may be outsourced. The nature of the coating is often very specific to the application environment and as such may vary from part to part. This could also be the case with other forms of chemical and heat treatment.

Many AM parts can include complex internal or difficult to reach features (e.g. the inside of a lattice). Should these features require finishing, it may be somewhat difficult to achieve a stable quality, even when using automated techniques. Some methods are under development to address these issues but more effort could be made and in fact most methods for surface finishing are highly manual in nature [99,171].

3.7. AM quality, inspection and certification

Many AM applications can be found in highly regulated industries, like aerospace and medicine. At this time, a large proportion of these applications are for series production, where the parts produced within the series are expected to be identical. This is even the case within the medical industry where one might expect such parts to be customised to suit a patient's needs and anatomy. The benefits are, in these cases, mostly related to geometric complexity (e.g. use of porous or lattice structures, part consolidation, etc.). Quality control, inspection and certification would therefore be conducted in a similar fashion to conventionally manufactured parts. Validation in these cases is as much about ensuring consistency in the manufacturing process and traceability of the supply chain as it is about the functionality of the part.

The US Federal Food and Drug Administration (FDA) is widely regarded as a key standards organisation around the world and many

other countries base their own medical standards on the FDA. In 2017 the FDA published guidelines related to technical use of AM in medical devices [60]. These guidelines cover aspects related to AM-based design of medical devices as well as how they are manufactured and validated. Certification of medical devices is required if there is a medium to high risk potential to the user. All implantable devices would be Class II or Class III (medium to high risk), whilst AM produced foot orthotics are class I, requiring no premarket notification to prove they have been clinically tested (i.e. no need for an FDA 510 (k) certification). It is therefore interesting to note that customisation is not explicitly connected to FDA certification.

The medical device manufacturer Stryker released their Spine Tritanium ® PL Cage around 2016. AM is used to create a complex porous geometry of titanium that aims to promote bone ingrowth in a lumbar spine fusion process. This device originally received FDA Class II certification but in Jan. 2019 a temporary product recall was announced based on some of the devices exhibiting fractures intraoperatively and postoperatively [100]. It is possible that introduction of this device may have been premature as it is believed that more experimental work is needed to establish the boundaries for fatigue in AM lattice structures [187]. It should be noted that similar porous and irregular lattice structures have been used in 100,000s of successful acetabular hip implant cases [68].

The above cases refer primarily to what the FDA calls Patient-matched Devices. This issue of possible failure will be even more important should the device have a customisable geometry. The FDA refers to these as Customised or Humanitarian-use devices. The limitation of use for these devices is that there is considered to be no substitute in the USA. These must also be limited in number and subject to significant medical board scrutiny. Medical authorities are currently at a significant cross-road as to how to provide custom implants for more widespread use [73].

Aerospace certification, through the Federal Aviation Authority, also appears to be at a similar cross-road. One major difference is that aerospace companies have the time benefit to carry out sufficient tests on prototypes prior to product launch. However, it is noted that many parts already in use could be repaired when damaged using AM techniques, most specifically using Directed Energy Deposition (DED). Many safety critical parts, like turbine blades, could be repaired in this way. Emphasis must therefore be on the AM process to ensure that functionality is maintained to a suitable standard [16]. Interior furnishings of commercial aircraft for example are however much less constrained and the onus is usually on the material in such cases. For example Air New Zealand are saving significant repair costs by making their own replacement seat tray-tables using materials like the flame-retardant ULTEM 9085 polymer material from Stratasys. This is just part of a much wider push to demonstrate a sustainable industry for AM in aerospace [92].

Many of the above issues for medical and aerospace are reflected in a more general form within the standards under development by ISO Technical Committee 261 in conjunction with the ASTM F42 Group. Numerous techniques, like the printing of test coupons alongside critical components, machine calibration and material storage, etc. are covered in detail under the auspices of these groups. This has led to significant improvements in process monitoring within industrial scale AM machines. Many polymer-based systems have camera monitoring that allow determining the build status and remote intervention if problems can be seen. Many metal L-PBF systems also have optional laser power and melt-pool sensing to determine the state of part with the possibility of detecting a failure before it damages the machine [6].

4. Tools and methods for designing lightweight parts

Lightweight design always has been a hot topic in structural engineering. AM processes can produce highly complex structures, constructed using both internally and externally very complex surfaces. More importantly, there is no clear relationship between the complexity of the part and the associated production cost [197], providing more freedom to explore the design space to its full extent. As a result, not only conventional lightweighting design tools are used for AM, but also some new methods have emerged to fully grasp the benefits of AM. In relation to lightweight design for AM, four groups of methods and tools can be identified: topology optimization (TO), generative design (GD), lattice structure filling, and bio-inspired design.

4.1. Topology optimization

Topology optimization was originally used for mechanical design problems to answer a layout optimization question: how to put the right material in the right place of a pre-defined design space? The objective was to obtain the expected mechanical properties at minimum material use. The method uses numerical analysis and design solution update steps in an iterative way, mostly guided by gradient computation or non-gradient discrete approaches [123].

Traditionally, TO is driven by an objective function, minimizing or maximizing while being subjected to a set of predefined constraints, such as mass, deformation, vibration frequency, etc. Usually, continuous design variables are used to solve the TO problem in a discretized way. During this optimization iteration process, segments of the predefined initial design space are step by step removed so as to arrive at the minimal part volume/mass. However, to obtain the optimal solution efficiently has been a challenge. To tackle this, density based methods (e.g. One-filed simplified isotropic material with penalization), topological derivatives (e.g. bubble method), level set methods and phased field methods have been developed. These methods all have specific pros and cons. More details, comparisons and comments on these methods can be found in [140]. The main difficulty is the complexity of mathematics, which forms an application barrier for mechanical or product designers.

Alternatively, people have tried to treat the TO problem directly using discrete approaches, e.g. using evolutionary approaches. Initial methods developed remove materials bit by bit using a strain energy distribution and a preset threshold value [43,177]. More advanced methods use genetic algorithms that both add and remove materials. This is called a bi-directional TO scheme [167]. Both types of methods show great potential for application in DfAM practice due to their ease of use and great applicabilty to generate beneficial complex structures e.g. porous structures and lattice structures, but with relaxed mathematical constraints.

As stated in [123], even current pure TO studies still face problems, such as efficiency, general applicability, ease of use, etc. Many of them only use relatively simple boundary conditions with limited constraints, e.g. mass. When introducing extra AM related constraints such as support structures/overhangs, minimum printable features, anisotropic material properties, heat-transfer, thermal strain/stress into TO, this would result in more complex constraints or boundary conditions. This again would result in more difficulties for the TO process to find the 'optimal solution' with an effective and fast converging simulation process. Attracted by the great potential of AM, researchers investigated TO with AM constraints, focussing on generating an optimal topologically lightweight material layout, to be printed without any manufacturing problems. Therefore, recent researches on TO for DfAM are geared towards print-ready designs bridging challenges in design and printing [140]. In general, there are two categories of methods proposed to deal with constraints in TO for AM. One is to represent AM constraints with mathematical models and embed them into the TO iteration process. The other is to use TO to generate one or a set of finite reference design solutions and apply design rules or experience to adapt these solutions manually or automatically to the AM constraints. This last category thus applies AM constraints in the post-processing stage of a given TO result.

For ease of practice, most of the earliest works directly tried to use existing traditional TO, or other similar structure optimization methods, for lightweight design in DfAM, without considering any AM constraints. The main reason for this was the assumption that AM can overcome manufacturing problems of TO generated structure as these structures would encounter in conventional manufacturing processes [188,189]. Although the 2D or 3D TO produced structures

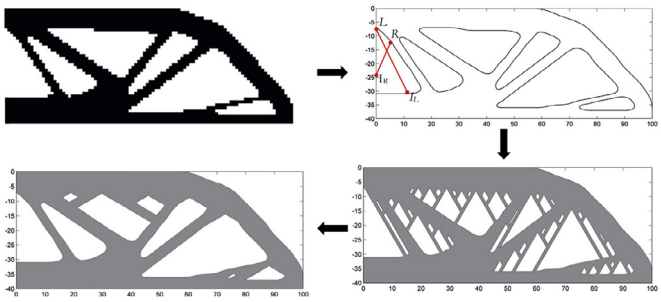

Fig. 7. Post-treatment of traditional TO result to avoid support structure for AM design [106].

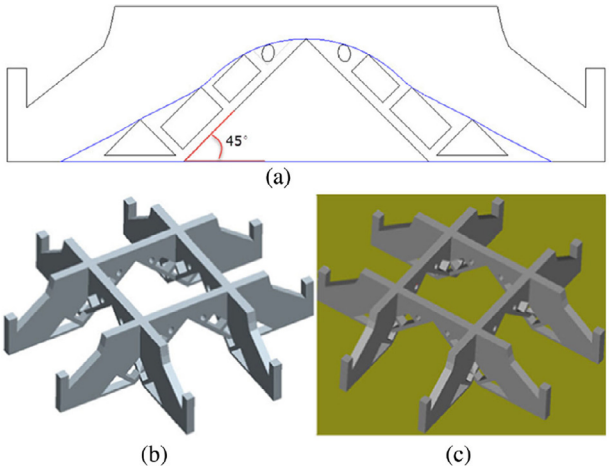

Fig. 8. 2D based 3D TO for AM design method via boundary decomposition: a. decomposition and filling method; b and c are alternative topology solutions [111].

could be printed by polymer AM processes, the direct application of the existing non-tailored TO may have difficulty using metallic AM. This is more complicated due to the multi-physical phenomena which cannot be handled by relatively simple macro mechanic and geometric based calculations. A large number of researchers began to associate specific AM constraints with their TO process, either as a TO process driver or a TO post-processor. However, their efforts are mainly focusing at 2D problems with consideration of only one simple or limited subset of AM constraints, e.g. support volume or overhang area. For example Leary et al. [106], describes a variant where traditional TO is conducted and a boundary decomposition algorithm is applied to detect and decompose the internal or external boundary areas needing support structures. Then, the detected and decomposed relatively large cavities are filled with a set of smaller generated boundaries so as to avoid the appearance of overhang as shown in Fig. 7.

In that example even though a sophisticated decomposition algorithm was designed and the use of support structure in printing was mostly avoided, the result is still far from optimal. 2D results sometimes are quite useless in practice since the broadened design freedom exists in 3D, not 2D. Taking the TO example in Fig. 7, we can easily rotate the 2D result around the X-axis in the 3D (simply make the vertical structure lay on the ground direction to print) and then we will find that there is no need of support structures. This means all the optimization steps are useless if we simply change the build orientation [202,203]. The dilemma may be caused by two factors: the TO researcher has a lack of knowledge on the AM processes or the direct embedding of AM constraints with mathematical models in the 2D or 3D TO processes is quite tough. Readers may find more representative research on 2D TO for AM lightweight design in [30,42,65,66,117,127,191]. To extend beyond 2D, researchers [111] adopted the decomposition method as proposed in [106] and tried to extend it to 3D TO for AM (Fig. 8). However, like the 2D cases presented above, reducing support structures is based on the compromise of adding more volume in the structure itself, which will

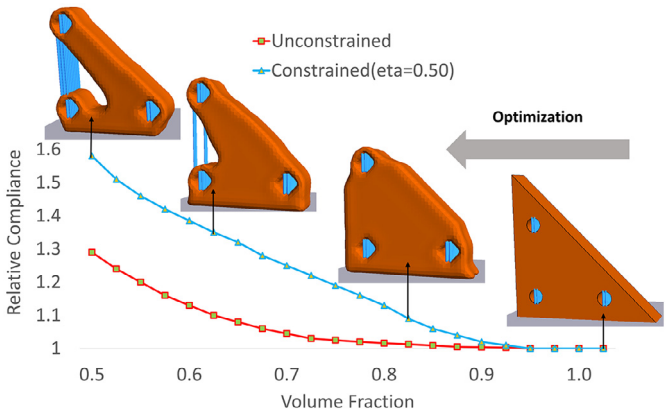

Fig. 9. (support volume) Unconstrained and constrained Pareto curves for three-hole bracket optimization [127].

decrease the global optimality. In addition, it is still not a real 3D TO for AM design since the decomposition and overhang angle control with volume filling still uses 2D operations.

`For these investigations discussed above, the 2D TO process is relatively easy to realize when only considering overhang or support structure AM constraint. However, complexity in AM is generally manifested in 3D. Hence, a lot of recent research is directed towards the development of tailored 3D TO methods for AM design. As is the case with the 2D variants, these 3D TO practices mainly focus on how to minimize overhang area or support volumes, as these constraints are relatively easy to integrate in the TO process. In [127], intensive discussions and experimental computations were conducted for the support volume constrained 3D TO for AM design. Level set based Pareto is adopted to control and alter the shape boundary where support structure may be required. It is hard to find a unique optimal solution, as each solution is a compromise between the constraints added. A set of Pareto solutions are provided, as seen in Fig. 9. It will be the designer's task to choose among these solutions, using the requirements and preferences from the application context. As stated in [127], the elimination of support volume may be possible but will hardly work for real 3D TO problems in AM design.

Even though it is hard to totally avoid the use of support structures, researchers in [102] still tried to obtain optimal 3D TO structures without supports for several relative simple demonstration cases (Fig. 10). To avoid the use of supports this study includes a simplified AM fabrication model, implemented as a layerwise filtering procedure into a topology optimization formulation. In this way, unprintable geometries (as overhang area) are excluded from the design space, resulting in fully self-supporting optimized designs. Similar ideas can be found in [2,122] where support constraint is applied. However, this as a compromise between the structural performance and global volume. The author of [102] also understands that it would be hard to avoid the use of support structure, and proposed to optimize the 3D structure with necessary support structure in parallel so as to obtain a better compromise [101]. In this study, two separate density fields were proposed to describe the component and support structure layouts respectively. A simple critical overhang angle was imposed into the TO process as a constraint. The examples

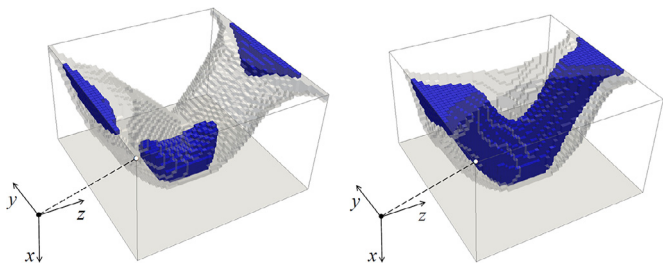

Fig. 10. Comparison between unconstrained and constrained 3D TO for AM [102].

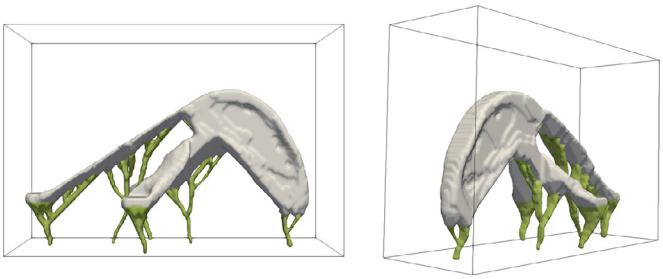

Fig. 11. Comparison between unconstrained and constrained 3D TO for AM [101].

presented in Fig. 10 and Fig. 11 show that more volume used for supports, which can be seen as waste material, results in more material saved for the main structure. Finding a suitable compromise here could result in added value. Actually, optimizing the functionality of supports for 3D structures to be printed by metallic AM processes would be a more important goal than optimizing material savings, since the support structures in metallic AM processes have a profound impact on the final printing quality [87]. This implies that when doing TO for AM design, we need to consider more constraints or embed more objective functions (for example take thermal distortion into account).

Another advancement in this direction is that researchers began to notice that the TO result has a critical link to the AM preprocessing steps, called micro AM CAPP (Computer-aided process planning) tasks in [196]. For example, the build orientation has a direct impact on the TO process since it determines the TO solution space. In [100], the combined optimization of part topology, support structure and build orientation is investigated. The research into these complex interrelationships (Fig. 12) are limited to 2D simple cases, where the impact of build orientation to TO and support optimization is clear. This implies that more work should be done in this direction for real 3D industrial cases. If we take the slicing and toolpath planning as additional considerations into the 3D TO process, the complexity would be increased even further. Finally, there are researchers working on level set TO methods to include AM material deposition path/toolpath as constraints to control sharp angles, deposition gaps, minimum inner hole size and minimum strut size in the topology formation process [114,115,176,193].

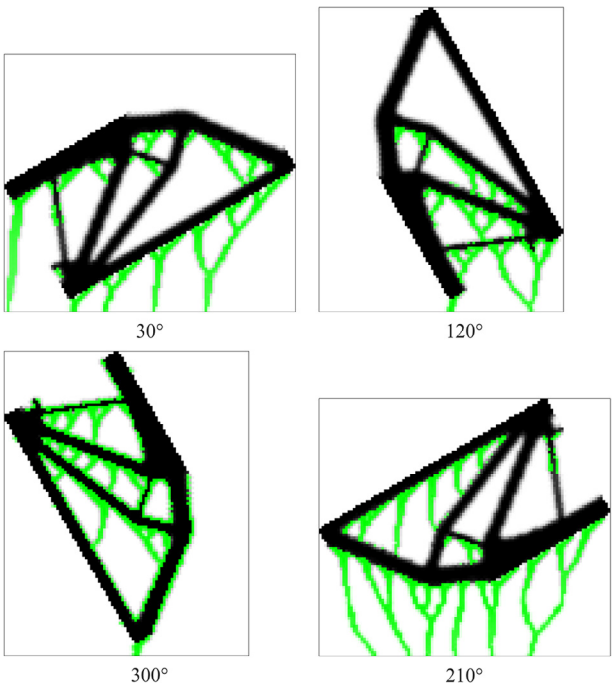

Fig. 12. TO for AM with AM build orientation constraints [100].

If the manufacturability of an AM TO solution could not be guaranteed, any kind of optimal design may bring no application value. In [3], manufacturability of the AM components and the cooling rate are considered as constraints and a shape based TO method is proposed. The manufacturability is checked for each layer. More recently, a new constraint function of the domain which controls the negative impact of porosity on elastic structures in the framework of shape and topology optimization is defined as a special shape derivative and proposed to embed into a level set TO process for AM lightweight design [121]. Even these methods can obtain a manufacturable TO layout, the 'rough boundary' problems brought by a density based TO method still pose challenges for AM processes. Therefore, level set based methods or boundary decomposition with spline interpolation are usually used to do post-processing of the TO results [123].

From the discussion of existing research presented above, there are still a lot of difficulties for the development of tailored TO methods and tools for AM lightweight design. The work discussed is all based on a single material showing isotropic properties. However, with digital controlled deposition, theoretically AM can print different materials with different gradients for multi-functional structures. For example, jetting-based AM processes can print smart structures with multiple polymers. Hence, TO methods and tools to help designers to allocate different material to different regions with optimal quantities for an expected multi-functional structure become critical. In [64,125], a multivariate SIMP (Solid Isotropic Material with Penalisation) method is proposed to optimize an application dependent multi-material layout. The inclusion of multiple materials in the topology optimization process has the potential to eliminate the narrow, weak, hinge-like sections that are often present in single-material compliant mechanisms. The demonstration example is the realization of a 3-phase, multi-material 2D compliant mechanism (Fig. 13). One can foresee that if some work in the future can help realize multi-material topology optimization for 3D metal structures, then the complexity capability of AM can be further explored not only for lightweight design but also for a combined multi-function design. Currently, metallic FDM process with metallurgical solidification as a post-process can theoretically realize the joining of multiple metals. Hence, this type of TO should develop to reach this future potential.

Although there still exists a lot of problems using current TO methods for AM in the academic community, the industrial side already shows big interest. There has been extensive exploration of TO for AM in diverse application examples either via standard TO tools or AM oriented tools. Reports have presented industrial design cases to show the great potential of TO tools for AM lightweight

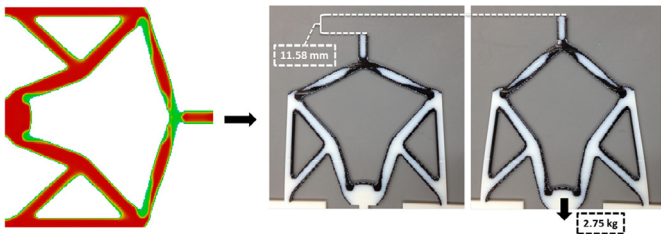

Fig. 13. Multi-material TO results for AM and a compliance mechanism case for testing. [64].

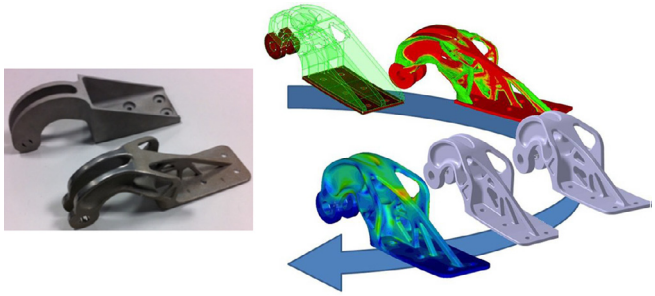

Fig. 14. Optimised Hinge. [81].

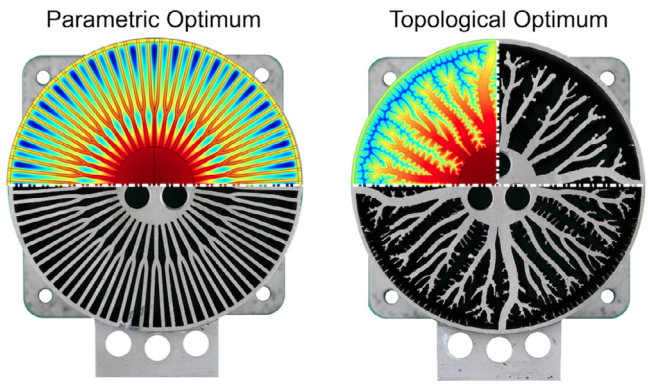

Fig. 15. The heat sink designs generated by parametric (left) and topology (right) optimization. [45].

design. EADS (European Aeronautic Defence and Space) presented a component for Airbus (Fig. 14). However, there are no details about how to embed the AM constraints in the design process of the example. In the second example, a minimum AM feature size is embedded into the density based TO process (pre-define a filter radius for the selective laser melting process) and allows to define arbitrary objective functions for multi-physic fields, which is crucial for gradient-based, and thus all topology optimization. An example on the comparison study of designing a heat sink between traditional parametric optimization and AM oriented TO is presented in Fig. 15.

Apart from density-based methods or level set methods, evolutionary TO methods were also investigated for AM design. In [1], a recently developed topology optimization method called Iso-XFEM (eXtended Finite Element Method) is used. This method is capable of generating high resolution topology optimized solutions using iso-lines/isosurfaces of a structural performance criterion. XFEM is similar to the BESO (bi-directional evolutionary structural optimization) method, but removes or adds materials within elements. However, there is no description how the TO process is tailored for AM. It is demonstrated that the TO result is applicable for L-PBF processes. It is not difficult to image that embedding AM constraints into an evolutionary TO process would be more difficult than that of density or level set based methods since the process uses discrete optimization. In addition, evolutionary based methods still have more difficulties in selection of stopping criteria or convergence analysis. The optimal design is usually hard to obtain due to the infinite solution space and the combinatory searching scheme.

As shown and discussed above, though some commercial tools are ready for use, very little AM constraints are considered. The current TO methods and commercialized tools still stay very close to the traditional TO tools. In addition, including both academic and industrial examples, those studies commonly lack experimental verification and there is no explicit agreement by the scientific community on their aspect ratio [140], which sets barriers for comparison and TO performance benchmarking. Therefore, there is still slot of work to be done for developing standard testing and experimental benchmarking examples. This holds also true for including more AM constraints so that TO results in optimal and qualified DfAM lightweight solutions.

4.2. Generative design

For the TO methods discussed above, people are trying to develop a fully automatic way to define a unique optimal lightweight structure design. However, it is difficult to converge to the optimal solution, especially when multiple objectives are set [200]. As investigated in [127], even when using only two objective functions, it is not easy to find all the Pareto solutions in evolutionary TO. Hence, a compromise should be made to sample the solution space when the theoretical global optimal could not be located. This introduces another design method for AM, generative design (GD). GD is a set of methods that apply a generative system, rule-based or algorithm-based, to explore the design space and generate candidate

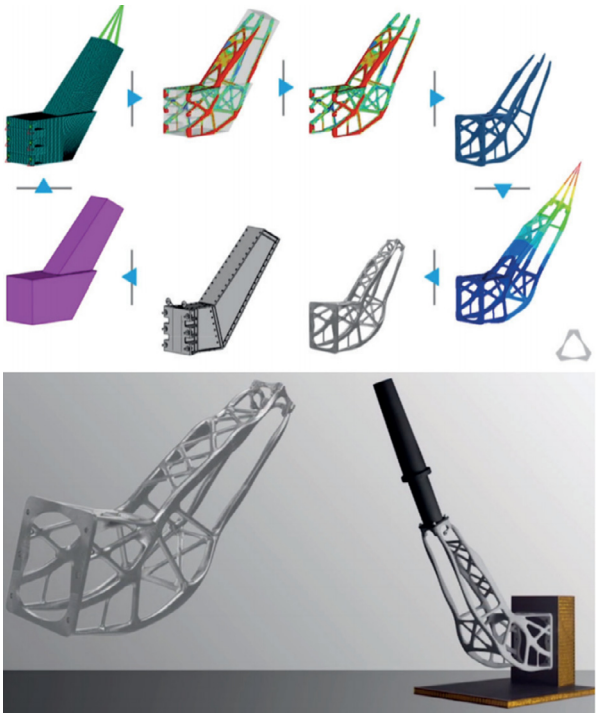

Fig. 16. Demonstration example of the generative design function [4].

solutions for designers. It is usually practiced for architectural design [152]. Generally, three types of methodologies can be recognized: 1. self-organization and self-assembly; consisting of large numbers of relatively simple, autonomous components that combine to construct large-scale artefacts or interact with one another to solve problems collectively; 2. evolutionary systems; based on simulating the process of natural selection and reproduction and 3. generative grammars; involving the specification of a mapping between a string of characters and the artefact to be designed (or its components) [124]. In structure design, we usually use the second method, applying evolutionary algorithms to sample and generate design solutions that are close to predefined objectives and criteria. Since TO also has evolutionary methods and is already adopted for AM design, e.g. in [1], it is easy to adapt to evolutionary generative design for AM. In current DfAM practice, multi-objective TO is used to populate a set of candidate solutions, usually non-dominated solutions, and then users/designers apply knowledge and KPIs to rank them for a final decision. Based on traditional TO methods, discretized version of the density based SIMP (Solid Isotropic Material with Penalisation) method [123], commercial software providers announced new functions of generative design for AM in their structure design tools and presented a couple of industrial design cases with numerical results [4,12]. For example, Fig. 16 gives one design example with a set of filtered candidate solutions.

Similarly, as TO, GD is not new, but introducing AM constraints in traditional GD is still difficult. Populating a set of finite candidate solutions for designers to select via predefined criteria is easy, but to ensure the validity of each populated candidate solution is complicated. To solve this problem, recently, researchers developed a new evolutionary generative design method for AM lightweight design to mimic termite behavior for volume construction [52,57]. The proposed methodology uses multi-agent algorithms that simultaneously design, structurally optimize and appraise the manufacturability of parts produced by additive manufacturing. Voxels are used to carry the design rules and manufacturing constraints for reasoning and combination during the geometry evolution process. In this way, very complex organic shapes can be populated (as shown in Fig. 17). However, this method considers support structures as the only AM constraint and has difficulty to include more.

For generative design for AM, there is still a lot of work to do to include more AM constraints and develop more efficient decision

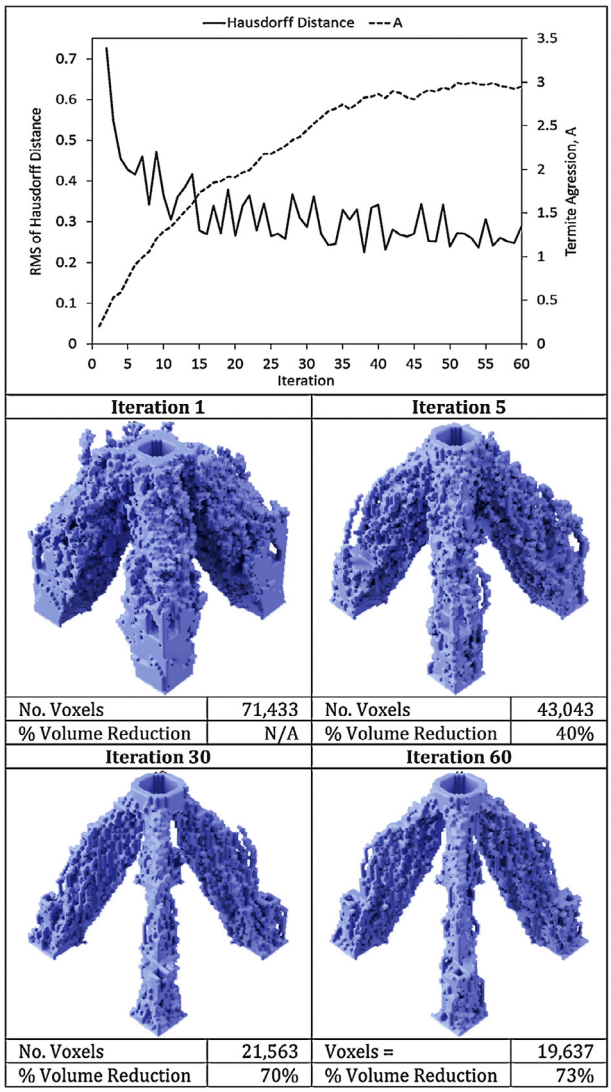

Fig. 17. A plot of the Hausdorff distance between consecutive design iterations and a value for each iteration. [53].

making tools to help designers define optimization criteria and candidate solution ranking schemes. Some commercial tools are now available however. On the other hand, when doing structure design via generative design methods, the global optimum and computational cost should be given attention. Recently, researchers began to combine TO with generative models, e.g., generative adversarial networks (GANs), and proposed a new concept, deep generative design, which owns the learning capability from the iteration process and existing design data [132]. These concepts hold the potential to better integrate existing AM processing knowledge (e.g. constraints, design rules and manufacturability) into the generative design procedure to populate and explore more qualified AM design solutions. However, it is still difficult for designers to evaluate candidate solutions with very little difference, especially for TO populated candidates with irregular shapes. Certainly, generative design is not only used for topology optimization but also can be applied to form synthesis, lattice and surface structure optimization and trabecular structures as a way to explore more design freedom using AM.

4.3. Lattice structure filling

Directly removing or adding material in the design space to search for the global optimal material topology solution is common to TO and generative design methods and, as stated above, there are many difficulties. As a compromise, generative design can include human knowledge to interactively select the candidate solutions so as to reduce the problem complexity. Another way of compromising is to

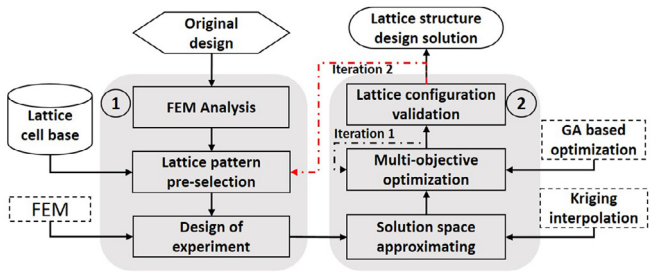

Fig. 18. Lattice configuration options for structure design. [107].

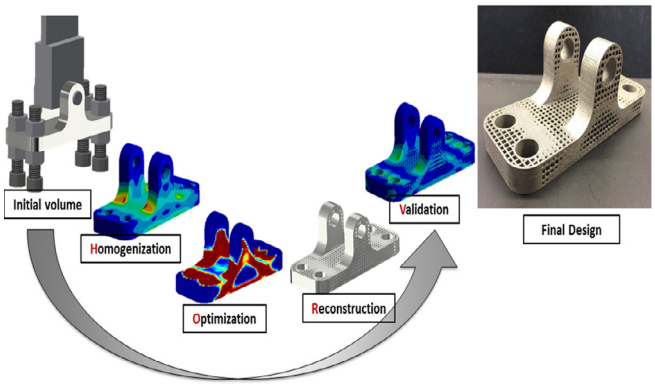

Fig. 19. Application of HMTO method to optimize the design of a pillow bracket with Ti64. [42].

approximate the optimal design solution with the filling of predefined unit structures, lattices or unit porous structures to replace solid volumes in an equivalent way. Therefore, this is an indirect lightweight design method for AM, which is also called lattice configuration [107], Fig. 18.

To obtain lattice structures, generally we have two approaches: 1. Homogenization and 2. Density based mapping. The former homogenizes the lattice structure as representative volume elements, like solid material. The lattice structures are similar to the micro porous for the traditional solid structure in homogenized volumes. In this way, special properties should be assigned to the representative volumes and then we can apply traditional TO or other structure optimization methods to operate the special volumes. Representative researches that apply this method can be found in [32,40,42,71,126] and Fig. 19 illustrates the general workflow.

The second approach maps the density values obtained from non-penalized TO results onto the explicit predefined lattice structures with optional adaptation to improve the approximation accuracy of mechanical response. Based on this approach, uniform or graded lattice structures can be obtained. Example studies can be found in

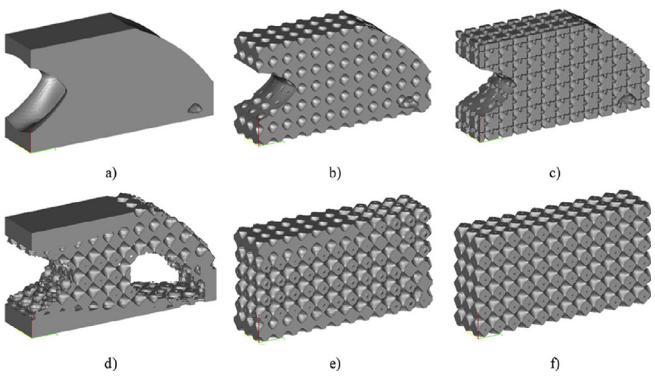

Fig. 20. Structures used for FEA: a) Solid (SIMP solution), b) Intersected Lattice of D-P, c) Intersected Lattice of BCC, d) Graded Lattice of D-P, e) Scaled Lattice of D-P, and f) Uniform Lattice of D-P. [135].

[89,135,192]. Fig. 20 shows an example where different predefined lattice structures are used to map the solid volume TO contours.

Although the two appraoches are not hard to understand, the operation and optimization of lattice structures is quite complicated, especially for large size structure design [107]. The first problem is the representation/digitalization of lattice structures. Usually, solid representation or surface representation can be used for individual lattice units. But when filled into solid hulls, the number of lattice units is very big, which makes the CAD file difficult to operate, including sweeping, meshing/mapping and tessellation. Secondly, when doing numerical simulation, the computation cost is much higher (a homogenization method may be better) since many more finite element units are required. Thirdly, when filling lattice structures into solid hulls, one needs to use uniform lattice in trimming or non-uniform lattice with conformal interface, which depends on specific design cases. Some researchers stated that conformal lattice structures have better structural performance than that of uniformed [89,170]. However, the operation of conformal lattice is more complicated and more difficult to control the manufacturability since they are not, like uniform lattices usually are, derived from benchmarking results. After that, the computation cost is a big issue, not only for the representation, but also for simulation and manufacturing [140]. That is why some researchers proposed to use kernel or symbolic representations for lattice units [13,158]. Finally, the most important challenge is how to obtain the global optimum when using lattice structures. As discussed above, using a lattice is already a compromise to the challenge of finding the global optimum. The approximation process further reduces the original design space and introduces more errors. Predefined and benchmarked limited lattice structures with fixed parameters are just a subset of the design variants. Actually, even for predefined lattice units, there are more parameters that can be modified and adjusted to specific design cases. Currently, many optimization studies for lattice structures are only limited to density, represented by strut diameter, and very little work focuses on parameter optimization and computation benchmarking for large lattice structure design cases [108]. Therefore, to be practical, current methods and tools from academic codes or commercial software tools all adopt knowledge based methods with TO methods for lattice filling. Usually, a lattice library is built to store predefined lattice units, benchmarked with numerical simulation or manufacturability analysis, and then a limited set of control options, concerning the lattice unit size, strut diameter, layout orientation, etc., are available for the filling operation. This is the main workflow of current (commercial) tools [48,104,131]. Fig. 21 gives a filling example.

As said before, although relatively small or medium sized lattice structures can be obtained, one not only sacrifices the stiffness but also it may be more difficult to search for the original global optimal lightweight design solution. If one only considers the lightweight effect in the design, lattice filling may not be the optimal choice. However, lattice structures can bring other benefits, e.g. energy absorption [141,157] and heat conduction [41] that solid structures may not have. This would be an important factor to encourage research and practice in the lattice domain.

5. Tools and methods for optimizing surface structure

As discussed above, the global optimal for structure design is usually hard to obtain. In those cases one may hope to find some solution existing in nature. Similar to lattice structures, which are made artificially, natural porous structures become a set of special elements to deal with specific design requirements. Examples include among others lightweight infill, porous scaffolds, energy absorbers, micro-reactors, heat conductors, or self-adaptating structures. These structures/functionalities have been known for some time, but due to the ability of AM to produce these complex structures, they now become part of the solution principles that can be applied by the product designer. Hence, the mimicking and post-processing of natural inspired or randomly generated complex topologies become a new design practice, which is called bio-inspired or biomimetic design. Its goal is to generate either lightweight structures with unexpected mechanical properties, similar to the lightweight design methods mentioned in the last section, or multi-functional surface structures as addressed here. This type of design is more difficult than that of relatively regular or conformal periodic lattice structures. Hence, the design and simulation focuses more on the form and shape of the surfaces while the mechanical properties and AM constraints are hard to consider due to their extreme complexity [62]. Generally, two design approaches, direct/indirect reproduction of natural topologies via reverse engineering and generic bio-inspiration using design rules or guidelines [54], are conducted in this domain. Both of the two need advanced geometric processing skills for topology representation and operation, which is either based on the approximation of numerous mesh units or the convergence of large numbers of unit shape functions.

Driven by the wide application in the medical domain, scaffolds and implants usually require similar internal surface topologies to the natural structures they are mimicing. This is in order to obtain optimal properties, e.g. cell spreading, strength distribution [110]. The main methods to generate irregular porous structures with complex internal surface topologies are either filling or hollowing materials from an initial design via specific algorithms. A representative filling method is Triply Periodic Minimal Surface (TPMS), which is an implicit surface with intricate structures. Researchers add different operation algorithms to do the filling with these surface units so as to approximate the original CAD model's skin [61,175,184,185]. A distance field controlled filling algorithm is presented in Fig. 22.

For the hollowing process, sub-volumes are generated via a set of specific algorithms within the original 3D CAD model and used to do Boolean operations. A shape function is applied in [36] to design a pore model and then a subtractive Boolean operation is conducted between the pore and the original solid CAD models to obtain the final scaffold model. The process is illustrated in Fig. 23. Similarly, a

Fig. 21. Hull filled with lattice structure [131].

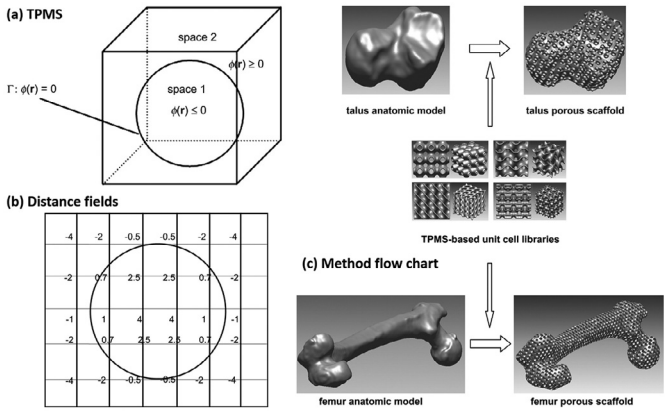

Fig. 22. Porous scaffold design by the distance field and surface models [184].

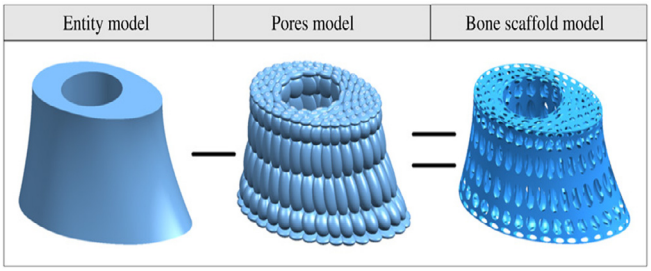

Fig. 23. Scaffold design method based on shape function and sphere pores [36]..

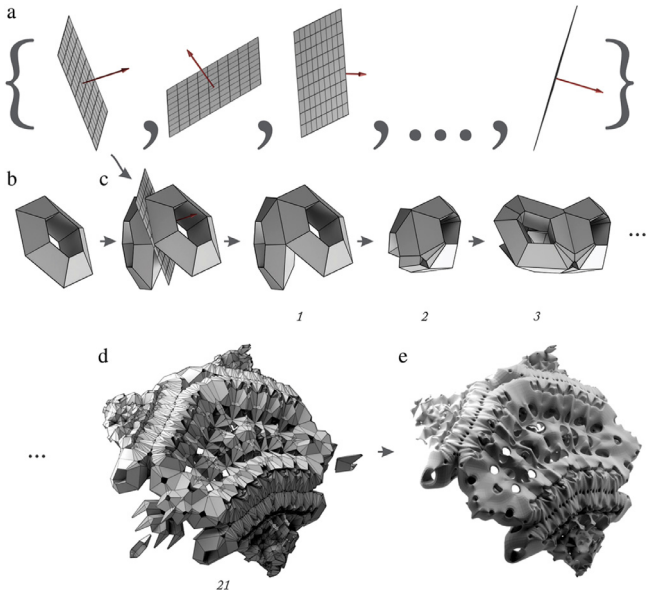

Fig. 24. A visual representation of the generative method. (a) a set of planes is generated as the underlying framework for all subsequent operations; (b) a user-guided input mesh is generated; (c) based on (b), a symmetrical mesh is generated; (d) the method is recursively applied and the result, following 21 iterations, is shown; (e) smaller sub-meshes are deleted and the subdivision surface is generated to produce the final artefact [14].

Voronoi tessellation method is adopted in [70] to do the material hollowing.

Apart from the internal surface structure generation, external surface structure design also attracts attention since using AM to print complex shapes for art or customized shapes has become popular. In artistic design, T-splines and Voronoi tessellation or predefined pattern bases are commonly used for defining complex surface topologies. In [14], a generative design method is applied to populate complex surface topologies via the use of predefined patterns. A recursive grammar is set for the generation of solid boundary surface models, suitable for a variety of design domains. Freeform 3D surface topologies can be formed by a set of 2-manifold polygonal sub meshes as shown in Fig. 24. More details about similar practices can be found in [182]. However, the optimization for artistic design is not so obvious.

To develop special surface structures for personalized casts/braces, a new topology optimization method is proposed in [186].

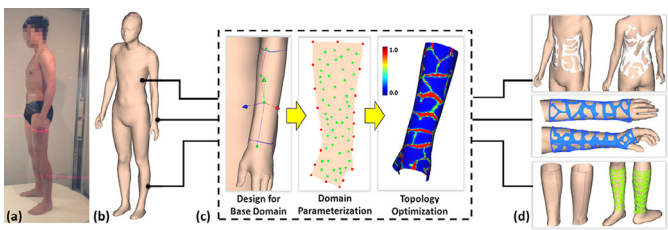

Fig. 25. A workflow for designing a custom compression cast/brace with custom-fit, lightweight and good ventilation [186].

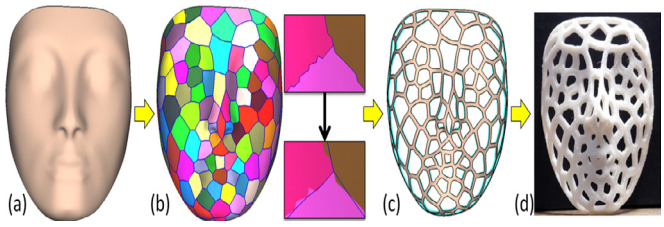

Fig. 26. (a) For an input face model, (b) a Centroidal Voronoi Diagram (CVD) [34] is computed, and the partition boundaries can be converted into styling curves. The generated curves are straightened [29] for better aesthetics. (c) Widening and thickening are applied, and (d) the result 3D printed [201].

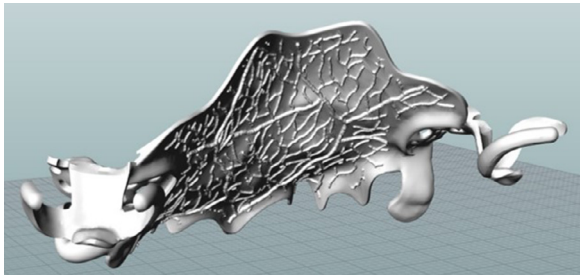

Fig. 27. functional surface structure a medical component for L-PBF process [204].

The novel TO method is based on thin plate elements on the two-dimensional manifold surfaces instead of 3D solid elements so as to reduce the computation cost for shape optimization. Fig. 25 gives an example of the proposed full method.

To decrease the threshold of customization of surface structure for the public when using AM, in [201], an interactive CAD design tool is proposed. This tool uses predefined reference unit models with the inputs of user's stylings to automatically generate customized hollowed surface topologies for fashion. Similar to other existing 3D porous structure design methods, this tool is mainly based on Voronoi tessellation and curve fitting methods. Fig. 26 shows the surface topology generation process.

The main advantage of this tool is that its predefined reference models can be benchmarked and tested to ensure manufacturability, which will avoid problems during AM. Similar to structure topology optimization, surface structure design and optimization face more difficulties in the modelling, simulation and embracing of AM constraints. Furthermore, irregular shapes pose more challenges for the computation cost of complicated geometric operations. This requires more work on the data structure, simulation driven analysis and optimization. A lightweight and convenient analysis platform should be developed to efficiently acquire the calculation results [62] for valid surface structure design and optimization. Currently, there is very little research invesigating the design guidelines of surface structure in AM. Most of the design pratices are limited at non-metallic AM processes. However, there is an ugent need in the medical application domain where special functional surface structures are critical. Fig. 27 presents a dental component where a bio-insipred surface structure with a special treatment function is printed using L-PBF. Reverse engineering is used to generate the surface structure. However, the modelling and function validation of such surface structure has not yet been studied. Hence, design methods and modelling tools should be developed to support the medical fabrication application for metal AM processes.

6. Manual optimization of internal part topology

One of the enablers within AM is the ability to optimize the internal part topology. In the previous sections automated topology optimization procedures for internal and surface part geometry were discussed. In many cases these automated methods are not required or applicable and other ways of defining the internal part topology are used.

With subtractive methods, structuring the product internal surfaces is hard or limited to very basic geometric features and production steps. Many of the commercially successful AM applications relate to internal transport of media (water, air, oil etc.) through the AM product. In relation to the additive manufacturing challenges, three subsets of AM features for internal transport of media can be identified; macro channel geometry, mini/micro channels and printed permeability. For macro channel geometry, down-facing surfaces of the channel may experience stability problems during printing. For mini/micro channels, the feature size may be close to the limitations of the printing device which may result in walls failing to print, channels being blocked and cumbersome removal of excess print material. Finally, AM permeable structures are created by ensuring process-induced porosity. Here the main challenge is finding stable process settings that allow for both the production of permeable and solid structures.

6.1. Internal geometry at macro level

In classical part production, channels for the transportation of viscous media are manufactured using conventional subtractive production methods like drilling, thus resulting in straight channels with round cross section and sharp corners. With the use of AM the location and shape of these channels can be optimized. In L-PBF and at macro level, the top surfaces of the round holes have the tendency to sag or collapse, and the cross section of the channel has to be optimized. Thomas [160] investigated the quality of produced channels and found that round holes up to a diameter of 7mm could be printed with minimal problems. Above that, sagging of the overhanging surface is noticed (Fig. 28, middle), as well as possible curl (Fig. 28, left), leading to recoater collisions. Other channel designs have been proposed (Fig. 28, right).

With the use of AM, cooling channels in injection molding (IM) inserts can be made conformal to the mold's product surface (conformal cooling channels) and located in areas critical to the quality of the die's function (see Fig. 29). Conformal cooling channels have been used to reduce cycle time and product warpage. Kitayama et al. [93] compared the effect of conformal cooling channels and conventional cooling channels for injection molding. Results showed an improvement of the cycle time of 53% and a reduction of product warpage by 46% compared to conventional cooling channels [91,93,137]. Although conformal cooling for IM is widely researched and benefits have been proven, actual application in industry lags behind. It is considered beneficial only for complex plastic geometries (thin walls and intricate features), that are difficult to cool quickly and uniformly and for very high production volumes [137]. Hölker [77] researched using conformal cooling channels in hot metal extrusion and also found significant production efficiency improvements.

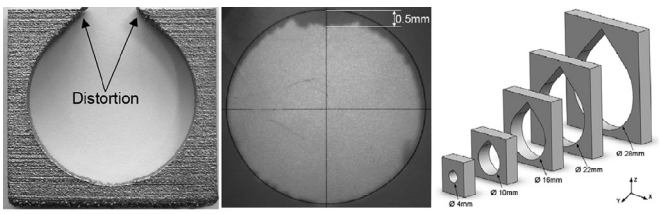

Fig. 28. Channel distortion (left, middle) and optimized channel design for channels of diameter 7mm and above [160].

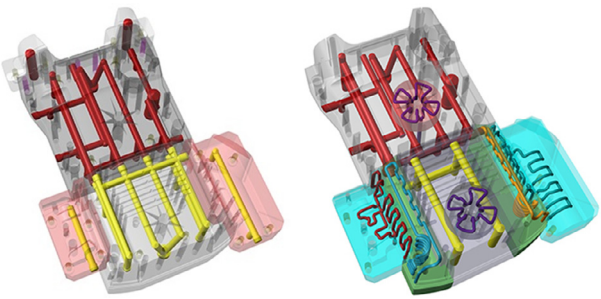

Fig. 29. Traditional (left) and conformal (right) cooling channel layouts for the production of plastic casings. [91].

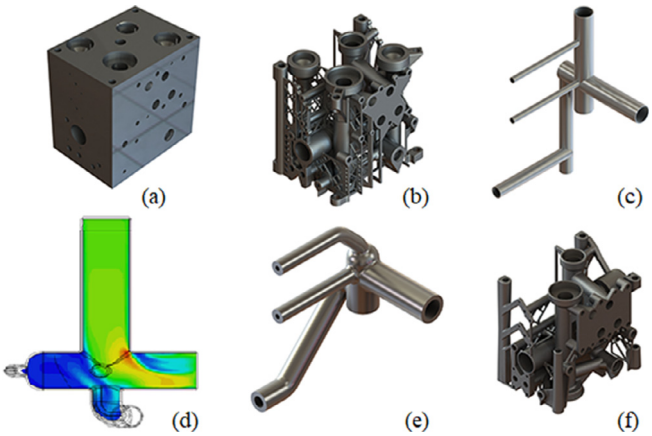

Fig. 30. Two stage manifold design process proposed by Renishaw. (a) Original design (b) Flow paths, wall thickness reduction and support geometry generation. (c) flow path extraction (d) CFD analysis of the flow paths (e) Optimized flow paths. (f) final manifold design [143].

Current research into manifold design has two main themes; mass reduction and flow optimization (see Fig. 30). Conventional methods create straight cooling channels, where connections result in pressure loss, increase the temperature and noise, which influences the reliability and lifetime of the system. Ma et al. [119] investigated multiple geometry adjustments which can be made when using AM. AM enables the design of fluent corners, smooth transitions between cooling channel diameters and the removal of unwanted drilling cavities, resulting in decrease in pressure loss by up to a factor of 3.

6.2. Mini and Micro internal geometry in AM

For mini and micro levels of geometry, used for transport of fluidic media, the minimal feature size of the AM technology chosen is often the limiting factor. Thomas [160] investigated some of these limits, for example as shown in Fig. 31. Printing of free standing walls and pilars is also a limiting factor as both the achievable minimal cross sectional area and maximal aspect ratio are limited [142].

In sectors like heating, ventilation, and air conditioning (HVAC), automotive, aero and electro-cooling, heat exchangers play a vital role in the energy efficiency. The heat transfer performance is dependent on the surface area to volume ratio.

Using mini and micro channels, this ratio can be increased, thus increasing the performance/mass ratio of the heat exchanger [163]. Arie et al. [7,8] investigated the performance of Ti64 (Fig. 32) air-water manifold-microchannel heat exchangers. Key to the intended efficiency increase was the production of thin fins ($< 300\ \mu$m) with high aspect ratio's (>10). Non AM-based production alternatives were considered slow, costly, not able to meet the aspect ratios or not possible to produce in the desired material. Compared to classical designs the manifold micro-channel show respectively 30–40%

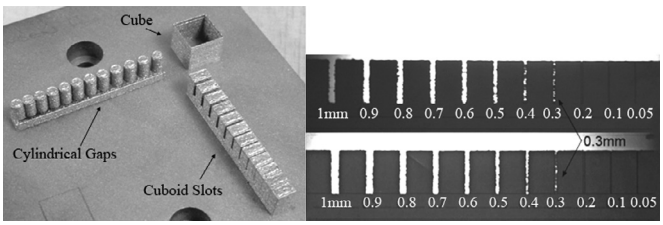

Fig. 31. Investigating the quality of the gap, for gap sizes of 0.1–1.0 mm, for printed cylinders and cubes. The right side shows a shadow image of the results (top image presents the cube structures, bottom the cylinders) [160].

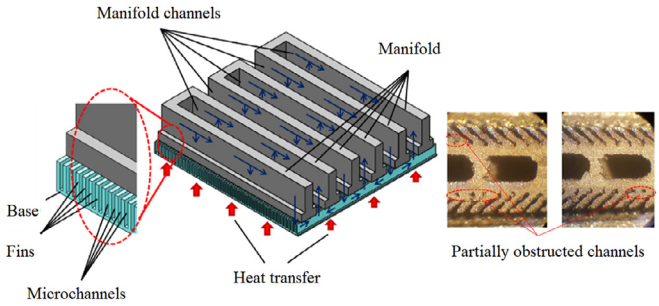

Fig. 32. Manifold/micro-channel structure from Arie et al [7,8].

performance increase in gravimetric heat transfer density. It was argued that inaccuracy of the production process reduced the manifold performance as some of the channels were blocked and the ideal fin thickness of 150 μm could not be realized. Meißner et al. [126] put the use of AM to a case study where they produced a highly integrated catalytic burner for auxiliary power units based on PEM-fuel cells. They used AM to produce the top and bottom manifolds which enabled them to integrate multiple functions into one device. This resulted in a volume reduction of 70% from 41L to 11L and a weight reduction of 60% from 30 kg to 12 kg.

6.3. Printed permeability

Calignano et al. [37] (Fig. 33) investigated the relation between material and process properties to fabricate both stochastic and non-stochastic porous structures. Parts were created using three different scanning strategies (x and y scanning lines, only x (or y) scanning lines, and rotating scanning patterns for each new layer) and by modifying the hatch distance h_d. It was found that hatch distances in excess of 0.20 mm were needed to be able to create distinct walls. Below that, wall formation was hampered by agglomeration of powder particles. Printing success was increased when lowering wall aspect ratios and not positioning walls parallel to the recoater movement direction. The rotating scanning strategy using h_d of 0.5 mm resulted in stochastic, foam-like structures, both with open and closed pores and porosity values of 43–45%.

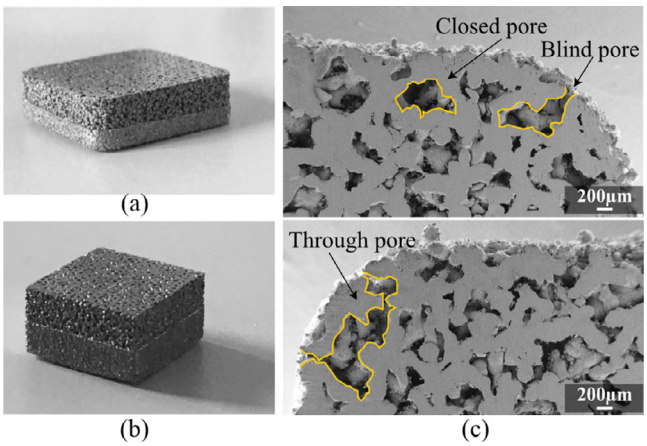

Fig. 33. Resulting foam like structures by varying scanning strategies and process settings. (a) AlSi10Mg (b) Ti6Al4V (c) resulting pore types.

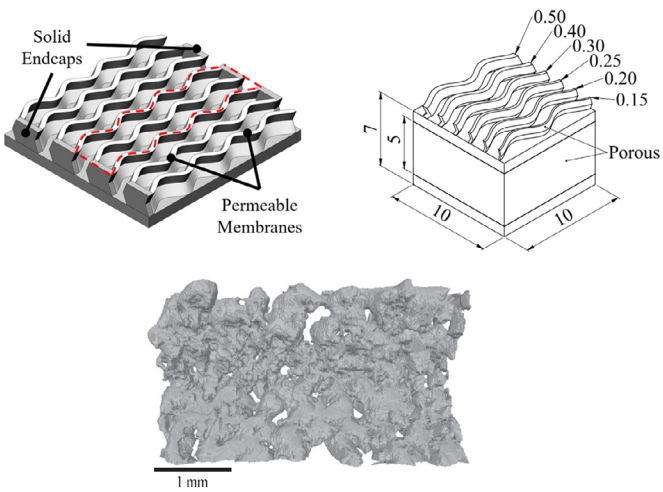

Fig. 34. Micro channel design with permeable layers (a), test geometry to find process settings to realize bulk and fin porosity (b) and resulting permeable wall with 23% bulk porosity (c) [44].

Collins et al. [44] investigated the use and production of a permeable membrane heatsink produced by AM (Fig. 34). In order to find the process settings that will result in permeable walls, test cubes were printed with fins on top with a height of 1 mm and wall thicknesses varying from 150 to 500 µm. The core of the cubes was used to determine bulk porosity (12–23%). All fins below 300 µm failed to print while 300 µm fins were successfully printed only for process settings resulting in low bulk porosity (<16%). The 400 and 500 µm fins printed successfully for all process settings used.

7. Functional material complexity

The design process can also consider that to solve some technological problems (like magnetic and non-magnetic materials) or to optimise some local properties (mechanical properties, surface properties for some joints), some processes allow building up multi-material objects or objects with material gradients. In some cases there has been significant progress although it increases the complexity of simulation and of process planning of AM-based value chains. In addition, there are no standard functionalities in the commercial software that could support such definitions, which must be managed manually or directly defined on the legacy software associated to specific processes. One basic functionality relates to material gradient of polymers and elastomer parts manufactured with voxel-based technologies. The design process criticaly addresses the local characteristics of the material for each voxel of the object. Another feature that is mostly used for metallic parts is lattice structure that could help in designing internal structures used to support the parts but also to minimize weight with respect to given functionalities.

In highly developed sectors for metal fabrication, in particular aeronautic and medical applications, AM processes use many metals like stainless steel, titanium, aluminum, cobalt chrome and nickel alloys [33,38,165]. An important feature of metal is its microstructure. For a given metal, there can be a variety of microstructural features that affect its mechanical properties [90]. The size of grains, micro-segregation of alloying elements, phases within the metal and size of dendrites relates to the tensile strength and ductility [118,172]. During the AM process, the microstructure is formed in-situ and would depend obviously on the process parameters and material used. The microstructure of metals determines the mechanical properties of the part such as yield strength, ductility and hardness [74,138,151,205]. Varying the process parameters like the energy sources and fill patterns can lead to differences in grain structure [63]. Such issues are both a very important potential advantage but also an additional complexity when considering the AM design process.

Functionally Graded Materials (FGMs) are defined as a class of advanced materials characterised by spatial variation in material composition across the volume, contributing to corresponding changes in material properties in line with the functional requirements [134]. The multi-functional status of a component is tailored through the material allocation at microstructure to meet an intended performance requirement. Microstructural gradation contributes to a smooth transition between properties of the material [120]. Another approach is based on Young's modulus variation for the determination of the mechanical properties' gradients, and consequently material microstructure or composition variations [136,145,170]. Another interesting proposition comes from [168] who proposes an interpretation of the material with intermediary

density as a lattice cellular structure that could be composed by several materials.

Homogeneous FGM composition creates porosity or density gradients by modulating the spatial microstructure or morphology of lattice structures across the volume of material through a voxel approach [5,78]. This method can be called "varied densification FGM". The directionality, magnitude and density concentration of the material substance in a monolithic anisotropic composite structure contributes to functional deviations such as stiffness and elasticity. The gradual transition from a solid exterior to a porous core leads to an excellent strength-to-weight ratio. Such representations are difficult to use when designing products with CAD software because of a lack of adapted representations. Even if new standards are partly addressing such models, the development of mathematical representations useful for both design and simulation is still in progress.

FGM can also address the aspect of multi-materiality through an approach of dynamically composed gradients or complex morphology [79]. The geometric and material arrangement of the phases controls the overall functions and properties of the FGM component. Multi-material FGM seeks to improve the interfacial bond between dissimilar or incompatible materials. Distinct boundaries can be removed through a heterogeneous compositional transition from a dispersed to an interconnected second phase structure, graded layers with discrete compositional parameters or smooth concentration gradients. Once again, material models are too complicated to be used for simulation. Demonstration and validation during the design phase of expected characteristics is still to be expected in a general manner.

But this is an interesting issue to be expected because, by fusing one material to another three-dimensionally using a dynamic gradient, the printed component can have the optimum properties of both materials. It can be transitional in weight, yet retaining its toughness, wear resistance, impact resistance or its physical, chemical, biochemical or mechanical properties [92]. Multi-material FGM can also provide location-specific properties tailored at small sections or strategic locations around pre-determined parts [164]. Some AM technologies are providing such opportunities. Construction of such parts could be of interest to solve design issues in order to avoid multi-part assemblies or complex joints for example.

Simulation models are still to be implemented and validated mostly because the design of heterogeneous compositional gradients are very complex. They can be divided into four types: a transition between two materials, three materials or above, switched composition between different locations or a combination of density and compositional gradation.

The key design parameters of FGM include the dimension of the gradient vector, the geometric shape and the repartition of the equipotential surfaces. The features and functionality of the component are further determined by the direction of the gradient within the material composition [47]. The design and types of the volumetric gradient can be classified according to 1D, 2D and 3D, and distribution of materials uniformly or through special patterns.

Defining the optimum material distribution function requires extensive knowledge of material data that includes the chemical composition, its characteristics and the manufacturing constraints [190]. At present, there are no design guidelines on material compatibility, mixing range for materials with variable and non-uniform properties and a framework for optimal property distribution such as choice of spatial, gradient distribution and the arrangement of transition phases is also lacking [156].

When generating graded components of high to low strength, the changing material properties brought about by modifications to the microstructure have to be carefully measured and quantified. Tamas-Williams [156] suggested two useful approaches to model the response of functionally graded components using the exponential law idealisation and material elements "Maxels". Finite Element Method (FEM) analysis can also be used to show and suggest an optimised set of elements under pre-determined circumstances to provide a better understanding of how the material properties will behave.

In order to generalise the use of FGM, it is crucial to understand the resulting differences between the predicted and real components. By knowing the required mix of properties, the required arrangement of phases, and compatibility of materials design rules and methods have to be established to avoid undesirable results. Knowledge of the "processing-structure-property" relationship can be gained through shared databases as a catalogue of material performance information [120].

Richards [144] first proposed a computational approach of using CPPN (Compositional Pattern Producing Network) encodings and a scalable algorithm using NEAT (Neuro Evolution of Augmented Topologies) to embed functional morphologies and macro-properties of physical features using multi-material FGM through voxel-based descriptions by a function of its Cartesian coordinates [155]. Some progresses are still expected but FGM or multi-material parts in general are being seriously considered as solutions for design evolution of products in the future. This is already used for polymers and elastomers and this is in progress for metallic products.

8. Assembly and part integration considerations

It is well recognized that it is possible to exploit the potential of additive manufacturing at product level. As one may infer by the existing standards [83–85], AM technologies already play a significant role not only for single parts but also at product level. Therefore, the classical Design for Assembly (DfA) approaches [25,31] have to be reconsidered in order to take advantage of these AM opportunities. An n-part product may be classified as static, movable, or compliant assembly and it may have components of the same or different materials. AM technologies enable the possibility to produce not only a single part of an assembly, but directly the assembled product. A full review of the direct fabrication of movable and compliant assemblies, also referred to as "non-assembly mechanisms", is given in [49]. This review shows many possible joints directly fabricated either using polymers or metals. Furthermore a deep discussion of polymer-based non-assembly mechanisms may be found in [50,109], proving that the polymer-based AM technologies are close to maturity for this kind of application.

Even though it is in its infancy, metal-based direct fabrication of assemblies is becoming relevant as shown in [26,37,49,79]. Fig. 35

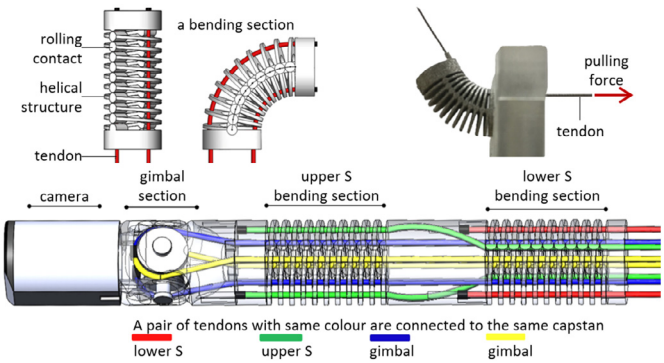

Fig. 35. Flexible metallic joint with 1-DoF bending and single-port surgical robot system design [79].

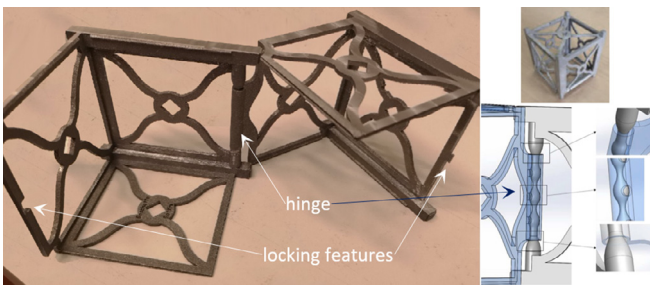

Fig. 36. Assembly features design and manufactured 1U CubeSat by SLM (AlSi10Mg) [26].

[79] shows a metallic compliant joint for a snake-like surgical robot, produced by PBF. In Fig. 36 [26], the detail design of a rotational joint and a snap-fit feature are shown for a nanosatellite metallic cubic structure fabricated by L-PBF.

But what about the design rules to fully exploit the AM technologies in assembly manufacturing? In the following, a brief analysis of the design rules and in particular of the part consolidation steps in designing a product will be considered.

8.1. Assembly design rules

As deeply discussed in [129,130], when dealing with assemblies and AM technologies, one main issue still to be adequately addressed is the geometrical product specification. In fact, no specific ISO-GPS or ASME-GD&T standard dedicated to AM processes exists, leaving design as a cumbersome process of defining geometrical requirements of assembly features or of single parts using a language dedicated to conventionally manufactured products.

Referring to an assembly with fixed connection type, general rules to design fasteners/connectors, in particular snap-fit features, are presented with respect to polymer-based AM processes in [85,94], and to metal-based ones in [26]. These general rules address issues on fastener/connector shape, wall thickness, gap width, staircase effect on sloped surfaces, and on the influence of anisotropy on the assembly product mechanical behavior.

Dealing with non-assembly mechanisms, design rules are discussed mainly referring to polymer-based AM processes like extrusion-based [76,128], material jetting [181], and vat photopolymerization processes [109]. The design rules refer to the minimization and the removal of the supports used during the non-assembly product fabrication, the effect of build orientation on the smoothness of the mechanism, and the selection of the clearance between assembled parts. Considering the latter issue, in [181] a benchmark is proposed to assess the lowest clearance limits for non-assembly mechanisms.

8.2. Part consolidation

Part consolidation is the first and most relevant step in (re)design for assembly. In a classical DfA approach [25] the designer should consider the following questions: Must parts move relative to each other? Must parts be of different materials? Must parts remain separate to enable/easy assembly/disassembly? If all the answers are no, the considered part could be combined with other parts in the assembly. But this is not the case when exploiting AM processes since they enable non-assembly mechanisms, multi-material printing, and easier functional integration. A significant example of AM part consolidation is the one reported in [146] (Fig. 37).

The original portable hydraulic manifold was used for in-situ testing of aircraft components, a 17-part assembly, and was completely redesigned as a single-part product, with 60% less weight, the same footprint, a 53% shorter height, and with a more reliable and robust design with respect to the original one, deeply exploiting a metal powder bed fusion technology. Nevertheless, the main outcome of the reported experience is the proposed redesign approach for part consolidation using metal AM (Fig. 38). The proposed approach is general, well structured, and detailed enough to be immedialtely applicable at industrial level, but it needs further testing on different case studies to prove the benefits.

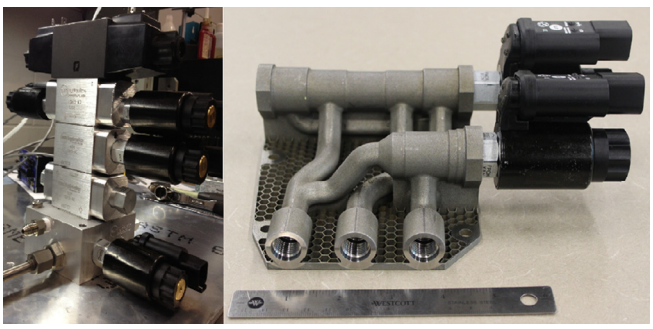

Fig. 37. Original (left) and redesigned (right) hydraulic manifold [146].

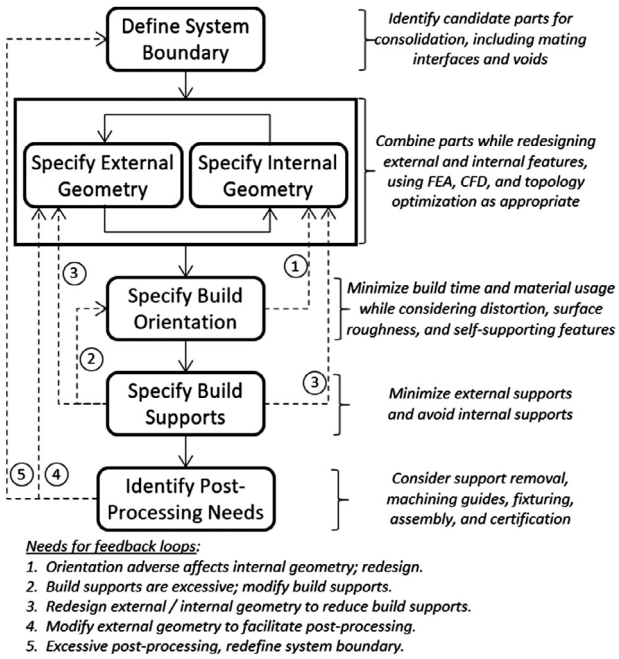

Fig. 38. Proposed (re)design approach for part consolidation [146].

An interesting framework to part consolidation and functional integration exploiting AM technologies is presented and validated in [180] (Fig. 39). In a further development of their approach, the authors have recently addressed the relevant problem of detecting the possible candidates for part consolidation, as reported in [179].

Potentially, when dealing with part consolidation, the designer may consider the need of part decomposition. The need to increase the number of parts in a product fabricated by AM may be due to many reasons: printability, productivity, functionality, artistry, and interchangeability. Printability is actually the main reason being related to the limited working envelope of AM machines. In [133] the

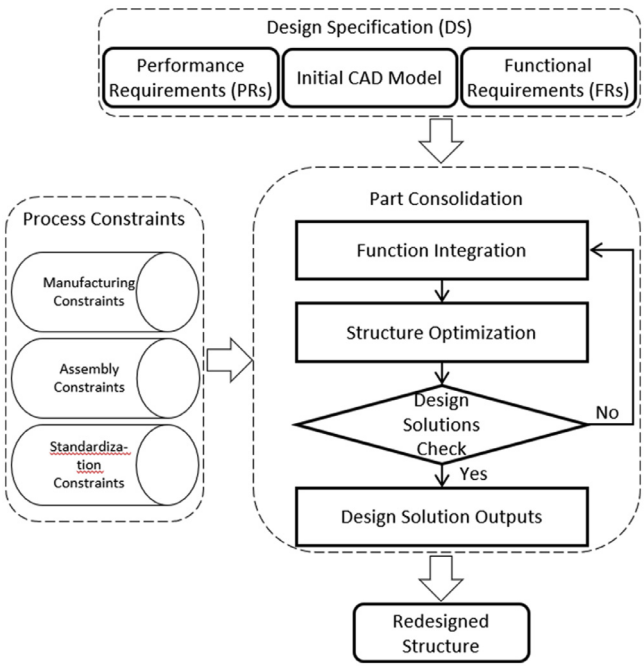

Fig. 39. Proposed part consolidation approach [180].

part decomposition problem in AM is addressed, but it is the first and unique example of research on this topic.

9. Conclusion and future challenges

DfAM is about design for the whole AM product life cycle. This paper has presented a framework of tools and methods for DfAM and has shown the strong interaction between these life cycle stages and AM product design. The state of the art was presented on many of these design tools and their applicability was illustrated using many of the latest examples from research and industry. But AM and DfAM is a field that is rapidly evolving, and many challenges still remain.

9.1. AM suitability exploration

A growing number of companies are exploring the commercial use of AM within their supply chain. For that, better methods and tools are needed to help the designer obtain an overview that identifies the (mis)match between functional and economical demands of the intended product and all stages of AM in product development. Methods for early cost estimation are lacking, while current figures for production cost per cm^3 are not based on established calculation methods and lack experimental and industrial verification. Late life cycle stages of postprocessing, inspection and certification have a significant impact on production cost and general applicability of AM, but these stages are underrepresented in current DfAM approaches. Finally, more education on (design for) Additive Manufacturing is needed, as the majority of product designers and engineers are still trained *to think subtractive*.

9.2. Product (Re)design for AM goals

Topology optimization enables strategies that go beyond lightweight design to include minimizing support usage and thermal deformation, optimizing local heat input, and with that the local material properties, porosity and strength. Much research is conducted in these areas, although most results have not reached maturity and are not yet available to the product designer. TO methods need further enhancement to tackle optimization as a 3D problem while taking all later product development stages into account. Generative design strategies have the benefit that they generate many possible design solutions, but as is the case with TO, few production and inspection constraints are currently integrated. Furthermore, methods and strategies should be developed to help the designer choose from the many, often very similar, design variants. Lattice structures show explicit benefits, especially in application fields involving energy absorption and heat conduction. They are however computationally intensive, which limits the optimization possibilities for large lattices to a limited set of parameters.

When looking at the part interior, specially designed porosity is seen as a promising new feature for internal transport of gasses and fluids. Both the optimal process settings as well as models for their application need further research to be applicable in everyday product design. To fully exploit the benefits of functional material complexity, further research must be conducted on rules and CAD representations of FGM related design intent.

During the last decade many efforts in proving the potential of AM technologies from the point of view of the product and not only of the single part/component. However, the development of design tools and methods is still a matter of basic research and far from industrial application. There is need for GPS/GD&T standards to define Product and Manufacturing Information in this selection, of general rules to define assembly features, and of approaches to integrate and consolidate parts of a product. The future of additive manufacturing is also looking towards 4D applications [88,154] where those challenges will be even more relevant.

For the final optimization of geometry so that it combines AM benefits with efficient production and inspection, a lot of research has been conducted. At an individual process level design knowledge is available and constantly being extended or refined. Further research is needed to enable improved integration in upstream product design steps like TO and generative design.

9.3. Further challenges

Regarding development of processing simulation models and methods. In future, it may be possible to directly embed these models into the geometry/topology definition procedure in DfAM if the computation cost is acceptable. Integrating processing and manufacturing with design in AM is feasible since the full digital chain is there. However, currently, this is still an open issue due to computational cost.

In current AM practice only a few zones in a product are defined where process settings can be defined, for example for the top and bottom facing surfaces and the bulk of the product in L-PBF. If machine learning and closed loop control can be used to define the optimal settings for each deposition area (e.g. laser pulse), the need for support structures as well as the effects of thermal stresses and deformations are expected to reduce/diminish. This will have large impact on the AM products and the way they are designed.

A combination of computational and knowledge-based methods (processing simulation case results, experimental benchmarking results, existing validated design solutions, etc.) would be an optimal solution for DfAM in the future to define qualified AM design solutions. Data analytic methods could be used to explore and discover knowledge from existing validated designs or dig out implicit knowledge from large industrial practice and experimental data sets.

A collaborative cloud-based DfAM platform would be more sustainable for the world if people could share their designs and design knowledge as well as other AM processing related data sets. This would enable and advance wide KBE in DfAM, save a lot of cost and time and improve quality over the trial and error practice in current DfAM.

Finally, developments in the processing field must have an effect on DfAM methods and tools. Further reduction of price per cm^3 of parts produced are expected. This is due to newer and faster production technologies. This will result in new application areas, new process constraints and new AM features.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Abdi M, Ashcroft I, Wildman RD (2018) Design optimization for an additively manufactured automotive component. *Int. J. Powertrains* 7(1–3):p142–p161.
[2] Allaire G, Dapogny C, Estevez R, Faure A, Michailidis G (2017) Structural optimization under overhang constraints imposed by additive manufacturing technologies. *J. Comput. Phys.* 351:p295–p328.
[3] Allaire G, Dapogny C, Faure A, Michailidis G (2017) Shape optimization of a layer by layer mechanical constraint for additive manufacturing. *Comptes Rendus Math.* 355(6):p699–p717.
[4] Altair (2019), Generative design and topology optimization for AM by Altair, https://cdn2.hubspot.net/hubfs/47251/Altair_Generative_Design_Report.pdf, Accessed 27 September 2019
[5] Amato K, Hernandez J, Murr L, Martinez E, Gaytan S, Shindo P (2012) Comparison of microstructures and properties for a Ni-base superalloy (Alloy 625) fabricated by electron and laser beam melting. *J. Mater. Sci. Res.* 1(2):3.
[6] Amini M, Chang S (2018) Process monitoring of 3D metal printing in industrial scale. In: *Proc. ASME 13th Int. Manufacturing Science and Engineering Conf.* TX, USA. College Station, , 2018.
[7] Arie M, Shooshtari A, Dessiatoun S, Ohadi M (2016) Performance characterization of an additively manufactured titanium. *14th International Conf. on Nanochannels, Microchannels, and Minichannels*, .
[8] Arie M, Shooshtari A, Ohadi M (2018) Experimental characterization of an additively manufactured heat exchanger for dry cooling of power plants. *Appl. Therm. Eng.* 129:187–198.
[9] Ashby M (2010) *Materials Selection in Mechanical Design*, fourth ed. Elsevier Science & Technology, 2010.
[10] ASTM, "BS ISO/ASTM 52910:2018; Additive manufacturing — Design — Requirements, guidelines and recommendations," DOI: 10.1520/F3154-18, 2018.
[11] Atzeni E, Salmi A (2012) Economics of additive manufacturing for end-usable metal parts. *Int. J. Adv. Manuf. Technol.* 62(9–12):1147–1155. https://doi.org/10.1007/s00170-011-3878-1.

[12] Autodesk (2019), Generative design for AM, https://www.autodesk.com/solutions/generative-design/manufacturing, Accessed 25 September 2019
[13] Azman A (2017) *Media Epidemics*: Method for Integration of Lattice Structures in Design for Additive Manufacturing, .
[14] Bader C, Oxman N (2016) Recursive symmetries for geometrically complex and materially heterogeneous additive manufacturing. *Comput.-Aided Des.* 81 (December 2016):39–47.
[15] Baldinger M (2016) *Supply chain management für additive manufacturing Konzepte, Werkzeuge und Prozesse für die Zusammenarbeit mit Dienstleistern zur Reduktion der Risiken beim Einstieg in additive Manufacturing* Phd thesis.
[16] Barbagallo J (2016) *Additive Manufacturing in Maintenance, Preventative Maintenance, and Alteration of Aircraft, Aircraft Engines, Propellors and Appliances*, US Dept. of Transportation Federal Aviation Administration, 2016.
[17] Bartolo P, Kruth JP, Silva J, Levy G, Mahlse A, Rajukar K, Mitsuishi M, Ciurana J, Leu M (2012) Biomedical production of implants by additive electro-chemical and physical processes. *CIRP Ann.* 61(2):635–655.
[18] Baumers M, Beltrametti L, Gasparre A, Hague R (2016) Informing Additive Manufacturing technology adoption: total cost and the impact of capacity utilization. *Int. J. Prod. Res.* .
[19] Baumers M, Dickens P, Tuck C, Hague R (2016) The cost of additive manufacturing: machine productivity, economies of scale and technology-push. *Technol. Forecast. Soc. Change.* 102:193–201.
[20] Baumers M, Tuck C, Wildman R, Ashcroft I, Rosamond E, Hague R (2013) Transparency built-in energy consumption and cost estimation for additive manufacturing. *J. Ind. Ecol.* .
[21] Baumers M, Tuck C, Wildman R, Ashcroft I, Rosamond E R, Hague R (2012) Combined build time, energy consumption and cost estimation for direct metal laser sintering. In: *Proceedings of 23th Annual International Solid Freeform Fabrication Symposium*, .
[22] Bayoumi A (2000) Design for manufacture and assembly: concepts, benefits and applications.. *Current Advances in Mechanical Design and Production VII Proceedings of the Seventh Cairo University International MDP Conference Cairo-Egypt*, 501–509.
[23] Berger R., Additive Manufacturing in Aerospace and Defense, www.rolandberger.com, available online2019
[24] Bikas H, Koutsoukous S, Stavropoulos P (2019) A decision support method for evaluation and process selection of Additive. *Procedia CIRP* 81:1107–1112.
[25] Boothroyd G, Dewhurst P, Knight A (2010) *Product Design for Manufacture and Assembly*, third ed. CRC Press. ISBN 9781420089271.
[26] Boschetto A, Bottini L, Eugeni M, Cardini V, Nisi G, Veniali F, Gaudenzi P (2019) Selective laser melting of a 1U CubeSat structure. Design for additive manufacturing and assembly. *Acta Astronaut.* 159:377–384.
[27] Bourell D, Kruth JP, Leu M, Levy G, Rosen D, Beese A, Clare A (2017) Materials for additive manufacturing. *CIRP Ann.* 66(2):659.
[28] Bournias-Varotsis A, Friel R, Harris R, Engstrøm D (2018) Ultrasonic Additive Manufacturing as a form-then-bond process for embedding electronic circuitry into a metal matrix. *J. Manuf. Processes* 32:664–675.
[29] Bournias-Varotsis A, Wang S, Hutt D, Engstrøm D (2018) The effect of ultrasonic additive manufacturing on integrated printed electronic conductors. *Electron. Mater. Lett.* 14:413 https://doi.org/10.1007/s13391-018-0053-y.
[30] Brackett D, Ashcroft I, Hague R (2011) Topology optimization for additive manufacturing. *In Proceedings of the Solid Freeform Fabrication Symposium*, Austin, TX348–362.
[31] Bralla J (1999) *Design for Manufacturability Handbook*, McGraw-Hill, New York1999.
[32] Brun E, Vicente J, Topin F, Ocelli R, Clifton M (2009) Microstructure and transport properties of cellular materials: representative volume element. *Adv. Eng. Mater.* 11:805–810.
[33] Brunette DM, Tengvall P, Textor M, Thomsen P (2012) *Titanium in Medicine: Material Science, Surface Science, Engineering, Biological Responses and Medical Applications*, Springer Science & Business MediaNew York.
[34] Bugatti M, Semeraro Q (2018) Limitations of the inherent strain method in simulating powder bed fusion processes. *Addit. Manuf.* 23:329–346.
[35] Busachi A, Erkoyuncu J, Colegrove P, Drake R, Watts C, Martina F (2016) Defining next-generation additive manufacturing applications for the Ministry of Defence (MoD). *Procedia CIRP* 55:302–307.
[36] Cai S, Xi J (2008) A control approach for pore size distribution in the bone scaffold based on the hexahedral mesh refinement. *Comput. Aided Des.* 40:1040–1050.
[37] Calignano F, Manfredi D, Ambrosio E, Biamino S, Pavese M, Fino P (2014) Direct fabrication of joints based on direct metal laser sintering in aluminum and titanium alloys. *Procedia CIRP* 21:129–132.
[38] Cantor B, Assender H, Grant P (2015) *Aerospace Materials*, CRC PressBoca Raton.
[39] Chekurov S, Metsä-Kortelainen S, Salmi M, Roda I, Jussila A (2018) The perceived value of additively manufactured digital spare parts in industry: an empirical investigation. *Int. J. Prod. Econ.* 205:87–97.
[40] Cheng L, Bai J, To A (2019) Functionally graded lattice structure topology optimization for the design of additive manufactured components with stress constraints. *Comput. Methods Appl. Mech. Eng.* 344:p334–p359.
[41] Cheng L, Liu J, Liang X, Albert C (2018) Coupling lattice structure topology optimization with design-dependent feature evolution for additive manufactured heat conduction design. *Comput. Methods Appl. Mech. Eng.* 332:p408–p439.
[42] Cheng L, Zhang P, Biyikli E, Bai J, Robbins J, To A (2017) Efficient design optimization of variable-density cellular structures for additive manufacturing: theory and experimental validation. *Rapid Prototyp. J.* 23:p660–p677.
[43] Claus M, Burkhardt S (1990) A new method of structural shape optimization based on biological growth. *Int. J. Fatigue* 12(3):p185–p190.
[44] Collins I, Weibel J, Pan L, Garimella S (2019) A permeable-membrane microchannel heat sink made by additive. *Int. J. Heat Mass Transf.* 131:1174–1183.
[45] Comsol (2019), Dimension,shape and topology optimization, https://www.comsol.com/optimization-module. Accessed 26 September 2019.
[46] Coykendall J, Cotteleer M, Holdowsky J, Mahto M (2014) 3D opportunity in aerospace and defense. *Additive Manufacturing Takes Flight*, Deloitte University Press.
[47] Craveiro F, Bartolo H, Bartolo P (2013) Functionally graded structures through building manufacturing. *Adv. Mater. Res.* 683:775–778.
[48] Crystallon (2019), http://www.food4rhino.com/app/crystallon. Accessed 20 September 2019
[49] Cuellar J, Smit G, Plettenburg D, Zadpoor A (2018) Additive manufacturing of non-assembly mechanisms. *Addit. Manuf.* 21:150–158.
[50] Dämmer G, Gablenz S, Hildebrandt A, Major Z (2019) PolyJet-printed bellows actuators: design, structural optimization, and experimental investigation. *Front. Robot.* AI 6. Article34.
[51] Desktop Metal, https://www.desktopmetal.com/, Accessed 4 November 2019
[52] Dhokia V, Essink W, Flynn J (2017) A generative multi-agent design methodology for additively manufactured parts inspired by termite nest building. *CIRP Ann.* 66(1):p153–p156.
[53] Digital Alloy. Digital Alloys' guide to metal additive manufacturing – Part 5. *Econ. Met. Addit. Manuf.* . https://www.digitalalloys.com/blog/economics-metal-additivemanufacturing/ Retrieved October.
[54] Du Plessis A, Broeckhoven C, Yadroitsava I, Yadroitsev I, Hands CH, Kunju R, Bhate D (2019) Beautiful and functional: a review of biomimetic design in additive manufacturing. *Addit. Manuf.* 27:p408–p427.
[55] Ecco, Innovation Lab ECCO presents Project Quant-U. Cooperate presentation November2017. https://group.ecco.com/en/news/newsroom/news/2017/innovation-lab. Available online October2018
[56] Engineering Live, Enhanced procedures for quality control in additive manufacturing, https://www.engineerlive.com/content/enhanced-procedures-quality-control-additive-manufacturing. Accessed online October 2019
[57] Essink W, Flynn J, Goguelin S, Dhokia V (2017) Hybrid ants: a new approach for geometry creation for additive and hybrid manufacturing. *Procedia CIRP* 60: p199–p204.
[58] ExOne 420 Stainless Steel data sheet, REV. 06/25/19, https://www.exone.com/ExOne/media/Materials-Binders/Data%20Sheets/Metal/X1_MaterialData_420SS_062519.pdfAccessed 4 November 2019
[59] Bechmann F (2014) Changing the future of additive manufacturing. *Met. Powder Rep.* 69(3):37–40.
[60] FDA. Technical considerations for additive manufactured medical devices. *Guidance for Industry and Food and Drug Administration Staff.* U.S. Department of Health and Human Services. Food and Drug Administration.
[61] Feng J, Fu J, Shang C, Lin Z, Li B (2018) Porous scaffold design by solid Tsplines and triply periodic minimal surfaces. *Comput. Methods Appl. Mech. Eng.* 336:333–352.
[62] Feng J, Fu J, Lin Z, Chang C, Li B (2018) A review of the design methods of complex topology structures for 3D printing. *Vis. Comput. Ind. Biomed. Art* 1:5 https://doi.org/10.1186/s42492-018-0004-3.
[63] Frazier WE (2014) Metal Additive manufacturing: a review. *J. Mater. Eng. Perform.* 23(6):1917–1928.
[64] Gaynor A, Meisel N, Williams C, Guest J (2014) Multiple-material topology optimization of compliant mechanisms created via PolyJet three-dimensional printing. *J. Manuf. Sci. Eng.* 136(6):061015.
[65] Gaynor A, Guest J (2016) Topology optimization considering overhang constraints: eliminating sacrificial support material in additive manufacturing through design. *Struct. Multidiscip. Optim.* 54(5):p1157–p1172.
[66] Gaynor A, Meisel N, Williams C, Guest J (2014) Topology optimization for additive manufacturing: considering maximum overhang constraint. *15th AIAA/ISSMO multidisciplinary analysis and optimization conference*, 2036.
[67] GE Additive, 3D Printing in the Oil and Gas Industry, https://www.ge.com/additive/additive-manufacturing/industries/oil-gas, Retrieved online October 2019
[68] GE Reports (2018), 100,000 patients later, the 3D-printed hip is a decade old and going strong, 5 March 2018. [Online]. Available: https://www.ge.com/reports/100000-patients-later-3d-printed-hip-decade-old-going-strong/. Accessed 20 august 2019.
[69] Goehrke S (2018) *Additive Manufacturing is Driving The Future Of The Automotive Industry*, Forbes www.forbes.com.
[70] Gómez S, Vlad M, López J, Fernández E (2016) Design and properties of 3D scaffolds for bone tissue engineering. *Acta Biomater.* 42:341–350.
[71] Gorguluarslan R, Gandhi U, Song Y, Choi S (2017) An improved lattice structure design optimization framework considering additive manufacturing constraints. *Rapid Prototyp. J.* 23:p305–p319.
[72] Gu H, Li L (2019) Computational fluid dynamic simulation of gravity and pressure effects in laser metal deposition for potential additive manufacturing in space. *Int. J. Heat Mass Transf.* 140:51–65.
[73] Guo X, Liu B, Lu Z (2019) Correlation between conditional approval and customized bone implant devices. *Orthopaed. Surg.* 11(1):10–14.
[74] Guo P, Zou B, Huang C, Gao H (2017) Study on microstructure, mechanical properties and machinability of efficiently additive manufactured AISI 316L stainless steel by high-power direct laser deposition. *J. Mater. Process. Technol.* 240:12–22.
[75] Hällgren S, Lars Pejryd L, Ekengren J (2016) 3D data export for Additive Manufacturing – improving geometric accuracy. *26th CIRP Design Conference, Procedia CIRP 50*, 518–523.
[76] Hallmann M, Goetz S, Schleich B, Wartzack S (2019) Optimization of build time and support material quantity for the additive manufacturing of non-assembly mechanisms. *Procedia CIRP* 84:271–276.
[77] Holker R, Haase M, Khalifa N, Tekayya E (2015) Hot extrusion dies with conformal cooling channels produced by additive manufacturing. *Mater. Today* 2(10-A):4838–4868.
[78] Hsiang Loh G, Pei E, Harrison D, Monzón M (2018) An overview of functionally graded additive manufacturing. *Addit. Manuf.* 23:34–44.
[79] Hu Y, Zhang L, Li W, Yang G (2019) Design and fabrication of a 3-D printed metallic flexible joint for snake-like surgical robot. *IEEE Robot. Autom. Lett.* 4 (2):1557–1563.

[80] Huis in 't Veld B, Ludger Overmeyer L, Michael Schmidt M, Wegener K, Malshe A, Bartolo P (2015) Micro additive manufacturing using ultra short laser pulses. *CIRP Ann.* 64(2):701.
[81] Hyperworks (2019), Maximizing the Potential of Additive Manufacturing, https://altairhyperworks.com/solution/Additive-Manufacturing. Accessed 25 September 2019.
[82] International Organization for Standardization. (2018). Additive Manufacturing-General Principles-Terminology (ISO/ASTM Standard No. 52900).
[83] ISO/ASTM 52910:2018Additive manufacturing — Design — Requirements, guidelines and recommendations
[84] ISO/ASTM FDIS 52911-1:2019 Additive manufacturing — Design — Laser-based powder bed fusion of metals
[85] ISO/ASTM FDIS 52911-2:2019 Additive manufacturing — Design — Laser-based powder bed fusion of polymers
[86] Jacob A, Wundhuber K, Ranke D, Lanza G (2018) Planning, evaluation and optimization of product design and manufacturing chains for new product and production technologies on the example of additive manufacturing. *28th CIRP Design Conference*, .
[87] Järvinen J, Matilainen V, Li X, Piili H, Salminen A, Mäkelä I, Nyrhilä O (2014) Characterization of effect of support structures in laser additive manufacturing of stainless steel. *Phys. Procedia* 56:p72–p81.
[88] Jian B, Demoly F, Zhang Y, Gomes S (2019) An origami-based design approach to self-reconfigurable structures using 4D printing technology. *Procedia CIRP* 84:159–164.
[89] Jin X, Li G, Zhang M (2017) Design and optimization of nonuniform cellular structures. *Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci.* 232:p1280–p1293.
[90] Tan JHK, Sing SL, Yeong WY (2019) Microstructure modelling for metallic additive manufacturing: a review. *Virtual Phys. Prototyp.* . https://doi.org/10.1080/17452759.2019.1677345.
[91] Karcher (2019) Renishaw conformal cooling solutions prove a boost to moulding productivity. *Addit. Manuf.* 15(8). [Online]. Available https://additivemanufacturing.com/2017/07/28/renishaw-conformal-cooling-solutions-prove-a-boost-to-moulding-productivity/ [Accessed 9/8/2019] .
[92] Kieback B, Neubrand A, Riedel H (2003) Processing techniques for functionally graded materials. *Mater. Sci. Eng* 362(1–2):81–106.
[93] Kitayama S, Miyakawa H, Masahiro T, Aiba S (2017) Multi-objective optimization of injection molding process parameters for short cycle time and warpage reduction using conformal cooling channel. *Int. J. Adv. Manuf. Technol.* 88 (5–8):1735–1744.
[94] Klahn C, Singer D, Meboldt M (2016) Design guidelines for additive manufactured snap-fit joints. *Procedia CIRP* 50:264–269.
[95] Klocke F, Klink A, Veselovac D, Keith D, Aspinwall K, Soo S, Schmidt M, Schilp J, Levy G, Kruth JP (2014) Turbomachinery component manufacture by application of electrochemical, electro-physical and photonic processes. *CIRP Annals* 63 (2):703–726.
[96] Kruth J (1991) Material incress manufacturing by rapid prototyping techniques. *CIRP Ann.* 40(2):603–614.
[97] Kruth J (1998) Progress in additive manufacturing and rapid prototyping. *CIRP Ann.* 47(2):525–540.
[98] Kruth J, Levy G, Klocke F, Childs T (2007) Consolidation phenomena in laser and powder-bed based layered manufacturing. *CIRP Ann.* 56(2):730.
[99] Kumbhar N, Mulay A (2018) Post processing methods used to improve surface finish of products which are manufactured by additive manufacturing technologies: a review. *J. Eng. Inst. India Ser. C* 99(4):481–487.
[100] Langelaar M (2018) Combined optimization of part topology, support structure layout and build orientation for additive manufacturing. *Struct. Multidiscip. Optim.* 57(5):1985–2004.
[101] Langelaar M (2019) Integrated component-support topology optimization for additive manufacturing with post-machining. *Rapid Prototyp. J.* 25(2):p255–p265.
[102] Langelaar M (2016) Topology optimization of 3D self-supporting structures for additive manufacturing. *Addit. Manuf.* 12:60–70.
[103] LASERTEC 65 3D hybrid, https://nl.dmgmori.com/products/machines/additive-manufacturing/powder-nozzle/lasertec-65-3d-hybrid, Accessed 4 November 2019
[104] Lattice Module 3-matic (2019), https://www.materialise.com/en/software/3-matic/modules/lattice-module. Accessed 20 September 2019.
[105] Leach R, Bourell D, Carmignato S, Donmez A, Senin N, Dewulf W (2019) Geometrical metrology for metal additive manufacturing. *CIRP Ann.* 68(2):677–700. 2019.
[106] Leary M, Merli L, Torti F, Mazur M, Brandt M (2014) Optimal topology for additive manufacture: a method for enabling additive manufacture of support-free optimal structures. *Mater. Des.* 63:678–690.
[107] Lebaal N, Zhang Y, Demoly F, Roth S, Gomes S, Bernard A (2019) Optimised lattice structure configuration for additive manufacturing. *CIRP Ann.* 68(1):p117–p120.
[108] Levy G, Schindel R, Kruth JP (2003) Rapid manufacturing and rapid tooling with layer manufacturing (LM) technologies, state of the art and future perspectives. *CIRP Ann.* 52(2):589–609.
[109] Li X, Zhao J, He R, Tian Y, Wei X (2018) Parametric design of scalable mechanisms for additive manufacturing. *J. Mech. Des.* 140. 022302-1/022302-19.
[110] Li Y, Li D, Lu B, Gao D, Zhou J (2015) Current status of additive manufacturing for tissue engineering scaffold. *Rapid Prototyp. J.* 21:747–762.
[111] Li Z, Zhang D, Dong P, Kucukkoc I (2017) A lightweight and support-free design method for selective laser melting. *Int. J. Adv. Manuf. Technol.* 90(9–12):2943–2953.
[112] Lindemann C, Jahnke U, Moi M, Koch R (2012) Analyzing product lifecycle costs for a better understanding of cost drivers in additive manufacturing. *Solid Freeform Fabrication Symposium, An Additive Manufacturing Conference At*, Austin, TX, USA23.
[113] Lipson H, Kurman M (2013) *Fabricated: The New World of 3D Printing*, Wiley Publishing.
[114] Liu J, To A (2017) Deposition path planning-integrated structural topology optimization for 3D additive manufacturing subject to self-support constraint. *CAD Comput. Aided Des.* 91:27–45.
[115] Liu J, Yu H (2017) Concurrent deposition path planning and structural topology optimization for additive manufacturing. *Rapid Prototyp. J.* 23:930–942.
[116] Liu R, Wang Z, Sparks T, Liou F, Newkirk J (2017) Aerospace applications of laser additive manufacturing. Laser Additive Manufacturing. Materials, Design, Technologies, and Applications. *Woodhead Publishing Ser. Electr. Opt. Mater.* : 351–371.
[117] Liu S, Li Q, Liu J, Chen W, Zhang Y (2018) A realization method for transforming a topology optimization design into additive manufacturing structures. *Engineering* 4(2):277–285.
[118] Lu J, Luo K, Zhang Y, Sun G, Gu Y, Zhou J, Ren X, Zhang X, Zhang L, Chen K (2010) Grain refinement mechanism of multiple laser shock processing impacts on ANSI 304 stainless steel. *Acta Mater.* 58(16):5354–5362.
[119] Ma M, Zhang H, Zhang J, Wang C (2018) Automatic design of hydraulic manifold block based on 3D. *First International Conference on Advanced Algorithms and Control Engineering*, .
[120] Mahamood R, E T, Akinlabi E (2017) Functionally graded materials. *Topics in Mining, Metallurgy and Materials Engineering*, Springer.
[121] Martínez-Frutos J, Allaire G, Dapogny C, Periago F (2019) Structural optimization under internal porosity constraints using topological derivatives. *Comput. Methods Appl. Mech. Eng.* 345:1–25.
[122] Mass Y, Amir O (2017) Topology optimization for additive manufacturing: accounting for overhang limitations using a virtual skeleton. *Addit. Manuf.* 18:58–73.
[123] Maute K, Sigmund O (2013) Topology optimization approaches: a comparative review. *Struct. Multidiscip. Optim.* 6.
[124] McCormack J, Dorin A, Innocent T (2004) Generative design: a paradigm for design research. In: *Proceedings of Future ground, Design Research Society*, .
[125] Meisel N, Gaynor A, Williams C, Guest J (2013) Multiple-material topology optimization of compliant mechanisms created via Polyjet 3d printing. *24th Annual international solid freeform fabrication symposium an additive manufacturing conference*, 28.
[126] Messner M (2016) Optimal lattice-structured materials. *J. Mech. Phys. Solids.* 96:162–183.
[127] Mirzendehdel A, Suresh K (2016) Support structure constrained topology optimization for additive manufacturing. *Comput.-Aided Des.* 81:p1–13.
[128] Moroni G, Syam W, Petrò S (2015) Functionality-based part orientation for additive manufacturing. *Procedia CIRP* 36:217–222.
[129] Moroni G, Petrò S, Polini W (2017) Geometrical product specification and verification in additive manufacturing. *CIRP Ann. – Manuf. Technol.* 66(1):157–160.
[130] Morse E, Dantan JY, Anwer N, Soderberg R, Moroni G, Qureshi AJ, Jiang X, Luc Mathieu L (2018) Tolerancing: managing uncertainty from conceptual design to final product. *CIRP Ann. – Manuf. Technol.* 67(2):695–717.
[131] Netfabb (2019), https://www.autodesk.com/products/netfabb/overview, Accessed date: 20/09/2019.
[132] Oh S, Jung Y, Kim S, Lee I, Kang N (2019) Deep generative design: integration of topology optimization and generative models. *J. Mech. Des.* 141(11).
[133] Oh Y, Zhou C, Behdad S (2018) Part decomposition and assembly-based (Re) design for additive manufacturing: a review. *Addit. Manuf.* 22:230–242.
[134] Oxman N, Keating S, Tsai E (2011) *Functionally Graded Rapid Prototyping, Mediated Matter Group*, MIT Media Lab.
[135] Panesar A, Abdi M, Hickman D, Ashcroft I (2018) Strategies for functionally graded lattice structures derived using topology optimisation for additive manufacturing. *Addit. Manuf.* 19:p81–p94.
[136] Park J, Sutradhar A (2015) A multi-resolution method for 3D multi-material topology optimization. *Comput. Methods Appl. Mech. Eng.* 285:571–586.
[137] Pecas P, Ribero I, Enriques E, Raposo A (2019) Additive manufacturing in injection molds—life cycle engineering for technology selection. *Adv. Appl. Manuf. Eng.* : 105–139.
[138] Peel M, Steuwer A, Preuss M, Withers P (2003) Microstructure, mechanical properties and residual stresses as a function of welding speed in aluminium AA5083 friction stir welds. *Acta Mater.* 51(16):4791–4801.
[139] Pei E, Monzón M, Bernard A (2019) *Additive Manufacturing – Developments in Training and Education*, Springer https://doi.org/10.1007/978-3-319-76084-1.
[140] Plocher J, Panesar A (2019) Review on design and structural optimisation in additive manufacturing: Towards next-generation lightweight structures. *Mater. Des.* :108164.
[141] Qiao P, Yang M, Bobaru F (2008) Impact mechanics and high-energy absorbing materials: review. *J. Aerosp. Eng.* 21:235–248.
[142] Redwood B., How to design parts for Metal 3D printing, https://www.3dhubs.com/knowledge-base/how-design-parts-metal-3d-printing/, Accessed online October 2019
[143] Renishaw, Hydraulic block manifold redesign for additive manufacturing. https://www.renishaw.com/en/hydraulic-block-manifold-redesign-for-additive-manufacturing–38949, Accessed online October 2019
[144] Robbins J, Owen S, Clark B, Voth T (2016) An efficient and scalable approach for generating topologically optimized cellular structures for additive manufacturing. *Addit. Manuf.* 12:296–304.
[145] Sanders E, Aguilo M, Paulino G (2018) Multi-material continuum topology optimization with arbitrary volume and mass constraints. *Comput. Methods Appl. Mech. Eng.* 340:798–823.
[146] Schmelzle J, Kline E, Dickman C, Reutzel E, Jones G, Simpson T (2015) (Re) Designing for part consolidation: understanding the challenges of metal additive manufacturing. *J. Mech. Des.* 137. 111404-1/111404-12.
[147] Schmidt M, Merklein M, Bourell D, Dimitrov D, Hausotte T, Wegener K, Overmeyer L, Vollertsen F, Levy G (2017) Laser based additive manufacturing in industry and academia. *CIRP Ann.* 66(2):561–583.
[148] Schmidt M, Levy G (2012) Quality management and estimation of quality costs for additive manufacturing with SLS. *Direct Digit. Manuf. Conf.* .

[149] Schneck M, Gollnau M, Lutter-Gunther M, Haller B, Schlick G, Lakomiec M, Reinhart G (2019) Evaluating the use of additive manufacturing in industry applications. *Procedia CIRP* 81:19–23.
[150] Senvol, http://senvol.com/database/, Accessed online October 2019
[151] Shuai C, Xue L, Gao C, Yang Y, Peng S, Zhang Y (2018) Selective laser melting of Zn-Ag alloys for bone repair: microstructure, mechanical properties and degradation behaviour. *Virtual Phys. Prototyp.* 13(3):146–154.
[152] Singh V, Gu N (2012) Towards an integrated generative design framework. *Des. Stud.* 33(2):185–207.
[153] Simpson T.W. (2019), After the build is done why do the bills keep coming? Retrieved October 2019https://www.additivemanufacturing.media/blog/post/postprocessing-steps-and-costs-for-metal-3d-printing
[154] Sossou G, Demoly F, Montavon G, Gomes S (2018) Design for 4D printing: rapidly exploring the design space around smart materials. *Procedia CIRP* 70:120–125.
[155] Steuben J, Illiopoulos A, Michopoulos J (2016) Implicit slicing for functionally tailored additive manufacturing. *Comput.-Aided Des.* 77:107–119.
[156] Tamas-Williams S., Todd I., (2016) Design for additive manufacturing with site-specific properties in metals and alloys, Scr. Mater.135:105−110.
[157] Tancogne-Dejean T, Spierings A, Mohr A (2016) Additively-manufactured metallic micro-lattice materials for high specific energy absorption under static and dynamic loading. *Acta Mater.* 116:14–28.
[158] Tang Y, Kurtz A, Zhao Y (2015) Bidirectional Evolutionary Structural Optimization (BESO) based design method for lattice structure to be fabricated by additive manufacturing. *Comput.-Aided Des.* 69:91–101.
[159] Tess (2016) Onkyo and Siemens launch line of bespoke 3D printed in-ear monitors, https://www.3ders.org/articles/20160914-onkyo-and-siemens-launch-line-of-bespoke-3d-printed-in-ear-monitors.htmlAccessed 04 November 2019
[160] Thomas D (2009) *The Development of Design Rules for Selective Laser Melting* Phd thesis. University of Wales Institute, 2009.
[161] Thomas-Seale L, Kirkman-Brown J, Attalla M, Espinoa D, Shepherd D (2018) The barriers to the progression of additive manufacture: Perspectives from UK industry. *Int. J. Prod. Econ.* 198:104–118.
[162] Thompson MK, Moroni G, Vaneker T, Fadel G, Campbell I, Gibson I, Bernard A, Schulz J, Graf P, Ahuja B, Martina F (2016) Design for additive manufacturing: trends, opportunities, considerations and constraints. *CIRP Ann.* 65(2):737–760.
[163] Tiwari R, Andhare R, Shooshtari A, Ohadi M (2019) Development of an additive manufacturing-enabled compact manifold. *Appl. Therm. Eng.* : 781–788147.
[164] Vaezi M, S, Chianrabutra S, Mellor B, Yang S (2013) Multiple material additive manufacturing—part 1: a review virtual and physical prototyping. *Virtual Phys. Prototyp.* 8(1):19–50.
[165] Vandenbroucke B, Kruth J-P (2007) Selective laser melting of biocompatible metals for rapid manufacturing of medical parts. *Rapid Prototyp. J.* 13(4):196–203.
[166] Vaneker T (2017) The role of design for additive manufacturing in the successful economical introduction of AM. *Procedia CIRP* 60:181–186.
[167] Virginia Y, Osvaldo Q, Steven G, et al. (1999) 3D and multiple load case bi-directional evolutionary structural optimization (BESO). *Struct. Optim.* 18(2−3):183–192.
[168] Vogiatzis P, Chen S, Wang X, Li T, Wang L (2019) Topology optimization of multi-material negative Poisson's ratio materials using a reconciled level set method. *CAD Comput.-Aided Des.* 83:15–32.
[169] Voxeljet industrial 3D printing systems, https://www.voxeljet.com/Accessed 4 November 2019
[170] Wang M, X Wang X (2004) Color level sets: a multi-phase method for structural topology optimization with multiple materials. *Comput. Methods Appl. Mech. Eng.* 193(6−8):469–476.
[171] Wang X, Li S, Fu Y, Gao H (2016) Finishing of additively manufactured metal parts by abrasive flow machining. In: *Proc. Solid Freeform Fabrication Symposium*, .
[172] Warren JA, Boettinger WJ (1995) Prediction of dendritic growth and micro segregation patterns in a binary alloy using the phase-field method. *Acta Metall. Mater.* 43(2):689–703.
[173] Weaver G. (2019), NDT in aerospace. Additive manufacturing and the inspection processeshttps://www.qualitymag.com/articles/95561-additive-manufacturing-and-the-inspection-processes. Visited online 28-10-2019
[174] Wohlers T, Gornet T (2014) *History of Additive Manufacturing*, Wohlers report.
[175] Wu J, Aage N, Westermann R, Sigmund O (2018) Infill optimization for additive manufacturing—approaching bone-like porous structures. *IEEE Trans. Vis. Comput. Graph.* 24:1127–1140.
[176] Xia Q, Shi T (2015) Constraints of distance from boundary to skeleton: for the control of length scale in level set based structural topology optimization. *Comput. Methods Appl. Mech. Eng.* 295:525–542.
[177] Xie Y, Grant P (1993) A simple evolutionary procedure for structural optimization. *Comput. Struct.* 49(5):885–896.
178 Wu B, z. Pan, Ding D, Ciuiri D, Li H, Xu J, Norrish J (2018) A review of the wire arc additive manufacturing of metals: properties, defects and quality improvement. *J. Manuf. Processes* 35:127–139.
[178] Yang S, Santoro F, Sulthan M, Zhao Y (2019) A numerical-based part consolidation candidate detection approach with modularization considerations. *Res. Eng. Des.* 30:63–83.
[180] Yang S, Tang Y, Zhao Y (2015) A new part consolidation method to embrace the design freedom of additive manufacturing. *J. Manuf. Processes* 20:444–449.
[181] Yap Y, Wang C, Sing S, Dikshita V, Yeong W, Wei J (2017) Material jetting additive manufacturing: an experimental study using designed metrological benchmarks. *Precis. Eng.* 50:275–285.
[182] Yap Y, Yeong W (2014) Additive manufacture of fashion and jewellery products: a mini review. *Virtual Phys. Prototyp.* 9:195–201.
[183] Yi L, Gläßner C, Aurich J (2019) How to integrate additive manufacturing technologies into manufacturing systems successfully: a perspective from the commercial vehicle industry. *J. Manuf. Syst.* 53:195–211.
[184] Yoo D (2011) Porous scaffold design using the distance field and triply periodic minimal surface models. *Biomaterials* 32:7741–7754.
[185] Yoo D (2013) New paradigms in hierarchical porous scaffold design for tissue engineering. *Mater. Sci. Eng. C* 33:1759–1772.
[186] Yunbo Z, Kwok T (2019) Customization and topology optimization of compression casts/braces on two-manifold surfaces. *Comput.-Aided Des.* 111:113–122.
[187] Zargarian A, Esfahanian M, Kadkhodapour J, Ziaei-Rad S, Zamani D (2019) On the fatigue behavior of additive manufactured lattice structures. *Theor. Appl. Fract. Mech.* 100:225–232.
[188] Zegard T. (2016) Educational Software - TOPslicer v0.8.4, http://zegard.com/software/2016, Accessed date: 20 September 2019.
[189] Zegard T, Paulino G (2016) Bridging topology optimization and Additive manufacturing. *Struct. Multidiscip. Optim.* 53(1):175–192.
[190] Zhang B, Jaiswal P, Rai R, Nelaturi S (2016) Additive manufacturing of functionally graded objects: a review. In: *Proc. of the ASME 2016 Int. Design Engineering Technical Conferences and Computers and Information in Engineering Conference IDETC/CIE 2016*, . August 21−24.
[191] Zhang K, Cheng G, Xu L (2019) Topology optimization considering overhang constraint in additive manufacturing. *Comput. Struct.* 212:86–100.
[192] Zhang P, Toman I, Yu Y, Biyikli E, Kirca M, Chmielus M, To A (2015) Efficient design-optimization of variable-density hexagonal cellular structure by additive manufacturing: theory and validation. *J. Manuf. Sci. Eng.* 137:1–8.
[193] Zhang W, Liu Y, Wei P, Zhu Y, Guo X (2017) Explicit control of structural complexity in topology optimization. *Comput. Methods Appl. Mech. Eng.* 324:149–169.
[194] Zhang Y, Bernard A, Harik R, Fadel G (2018) A new method for single-layer-part nesting in additive manufacturing. *Rapid Prototyp. J.* 24(5):840–854.
[195] Zhang Y, Bernard A (2014) Grouping parts for multiple parts production in Additive Manufacturing. *Procedia CIRP* 17:308–313.
[196] Zhang Y, Bernard A (2018) A KBE CAPP framework for qualified additive manufacturing. *CIRP Ann.* 67(1):467–470.
[197] Zhang Y, Bernard A, Gupta R, Harik R (2014) Evaluating the design for additive manufacturing: a process planning perspective. *Procedia CIRP* 21:144–150.
[198] Zhang Y, Bernard A, Harik R, Karunakaran K (2017) Build orientation optimization for multi-part production in additive manufacturing. *J. Intell. Manuf.* 28 (6):1393–1407.
[199] Zhang Y, Gupta R, Bernard A (2016) Two-dimensional placement optimization for multi-parts production in additive manufacturing. *Robot. Comput.-Integr. Manuf.* 38:102–117.
[200] Zhang Y, Wang W, Bernard A (2016) Embedding multi-attribute decision making into evolutionary optimization to solve the many-objective combinatorial optimization problems. *J. Grey Syst.* 28(3):124–143.
[201] Zhang Y, Kwok T (2017) An interactive product customization framework for freeform shapes. *Rapid Prototyp. J.* 23(6):1136–1145.
[202] Zhang Y, Bernard A, Harik R, Karunakaran K (2017) Build orientation optimization for multi-part production in additive manufacturing. *J. Intell. Manuf.* 28 (6):1393–1407.
[203] Zhang Y, Harik R, Fadel G, Bernard A (2019) A statistical method for build orientation determination in additive manufacturing. *Rapid Prototyp. J.* 25(1):187–207.
[204] Zhang Y, Wang Z, Zhang Y, Gomes S, Bernard A (2020) Bio-inspired generative design for support structure generation & optimization in AM. *CIRP Ann. – Manuf. Technol.* 69/1.
[205] Ziętala M, Durejko T, Polański M, Kunce I, Płociński T, Zieliński W, Łazińska M, Stępniowski W, Czujko T, Kurzydłowski KJ (2016) The microstructure, mechanical properties and corrosion resistance of 316 L stainless steel fabricated using laser engineered net shaping. *Mater. Sci. Eng.* 677:1–10.