Additive Manufacturing Enabled Design Theory and Methodology: A Review

Sheng Yang • Yaoyao Fiona Zhao

Abstract As Additive Manufacturing (AM) process evolves from rapid prototyping to the end-of-use product manufacturing process, manufacturing constraints have largely been alleviated and design freedom has been significantly broadened, including shape complexity, material complexity, hierarchical complexity and functional complexity. Inevitably, conventional Design Theory and Methodology (DTM) especially life-cycle objectives oriented ones are challenged. In this paper, firstly, the impact of AM on conventional DTM is analyzed in terms of Design for Manufacturing (DFM), Design for Assembly (DFA), and Design for Performance (DFP). Abundance of evidences indicate that conventional DTM is not qualified to embrace these new opportunities and consequently underline the need for a set of design principles for AM to achieve a better design. Secondly, design methods related with AM are reviewed and classified into three main groups, including design guidelines, modified DTM for AM, and Design for Additive Manufacturing (DFAM). The principles and representative design methods in each category are studied comprehensively with respect to benefits and drawbacks. A new design method partially overcoming these drawbacks by integrating function integration and structure optimization to realize less part count and better performance is discussed. In the mean time, the review also identified the possible areas for future research.

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Keywords Additive manufacturing · Design Theory and Methodology · Function integration · Part consolidation

1 Introduction

Since the first reported design research conducted by Reuleaux in 1861 and 1875 [1,2], DTM has been intensively studied. A classic view of DTM is given as "Design theory is about how to model and understand design; however, design methodology is about how to design, more precisely a design process model with logical consequential phases in which a design task is completed to develop product specifications" [3]. DTM centralizes on modeling design process and theoretical abstraction of design knowledge. Whereas, current product structures determined by these design methodologies are iteratively compromised in functionalities and performance due to the inherent limitations of conventional manufacturing technologies [4]. For example, part consolidation as an effective way to reduce part count and consequential process time and cost, has been intensively studied in DFX such as DFA, Design for Disassembly (DFD), and Design for Manufacture and Assembly (DFMA). The problem is that the design freedom of part consolidation is heavily stifled by the requirement of DFM and by the available structure optimization method; therefore, a global optimal consolidated structure is not achieved. As AM process evolves from rapid prototyping to the end-of-use product manufacturing process, manufacturing constraints are largely alleviated and the design freedom is extremely expanded. For example, conventional design limitations such as uniform wall thickness, avoiding sharp corners, and minimising weld lines in injection moulding can be overcome by AM [5].

AM is defined by the American Society for Testing Materials (ASTM) as a "process of joining materials to make object from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" [6]. From a manufacturability perspective, the benefit of employing AM process (also well known as Rapid Manufacturing (RM) at the beginning) is the ability to virtually manufacture parts of any geometric complexity without tooling, which used to be one of the typical restrictive factors for today's product development [7]. Numerous literature can be found in this stage focusing on just exploring what AM can fabricate without any design rules or methods, such as part redesign [8,9] , part customization [10,11] and industrial design [12,13]. From a design perspective, the advantage of AM over conventional subtractive or formative methods is well illustrated by the great design freedom. These design freedoms enabled by AM capabilities are reflected in the following four categories: shape complexity, hierarchical complexity, material complexity and functional complexity [14].

- Shape complexity: it is possible to manufacture virtually any shape, which means that lot size of one is practical, customized geometries are achieved readily, and shape optimization is enabled.
- Hierarchical complexity: hierarchical multi-scale structures can be designed and fabricated from the microstructure through geometric mesostructure (0.1~10mm) to the part-scale macrostructure. Basic idea of hierarchical structures is that features at one size scale can have smaller features added to them, and each of those smaller features can have smaller features added.
- Material complexity: material can be processed one point, or one layer, at a time, enabling the manufacture of parts with complex material compositions and designed property gradients.
- Functional complexity: when building parts in an additive manner, the inside of the part is always accessible. This makes it possible to intensively integrate multiple design domains to realize multi-functionalities. For example, operational mechanisms and embedded components can be fabricated directly to achieve multifunctional parts.

These four aspects of design freedom are not independent. For example, functional complexity can be also achieved by adopting hierarchical structures. In the research of Watts and Hague et al. [4], a heterogeneous structure made from a single material is accomplished by simultaneously considering various cellular structures and densities other than by Functional Graded Materials (FGMs).

Although AM process has extremely reduced the need of taking much consideration for manufacturing constraints, AM process does have some current issues. These issues can be listed but not limited to available materials, geometric limitations (such as minimum wall thickness and minimum clearance [15]), dimensional accuracy [16] and surface roughness, support design and removal for some techniques like Selective Laser Sintering (SLS), low mechanical properties (for example Material Jetting process [17]), building time for large size component, and material recycling (i.e. FGMs [4]). However, with technique progress, these issues can be solved. Therefore, the manufacturing constraints of AM process are not discussed in this paper.

To better understand how to take full advantage of design freedom enabled by AM process, the impact of AM on conventional DTM is comprehensively analyzed in section 2. Then, a detailed literature review of AM related design methods is summarized in section 3. In section 4, a new AM enabled design method is proposed to preliminarily incorporate process knowledge and structure optimization into design process from the perspective of function integration and better performance. Finally, this paper is wrapped up with conclusions and possible future research.

2 Impact of AM on conventional DTM

Since DTM covers such a whole spectrum of design theories and methodologies, it is difficult to analyze the impacts of AM on all the design theories and design methods. It is asserted that the most useful and practical theories and methodologies are characterized by mathematic foundation, concrete objectives, or explicit process [3]. Hence, this paper narrows the scope into analyzing the very DTM which matches these characteristics. According to the classification method proposed by Tomiyama [18] based on the General Design Theory (GDT) [19], representative design methodologies such as Axiomatic Design [20], Pahl and Beitz design flow method [21], Design for X (DFX), Adaptable Design [22], Characteristics-Properties Modeling (CPM) [23], and Contact and Channel Model (C&CM) [24], all belong to the second category. This category is called DTM to enrich attributive and functional information of design solutions. The other two categories are the DTM to generate a design solution and the DTM to manage design and represent design knowledge. AM exerts an influence on all these three categories. How to generate a design solution is changed by functional complexity because more functions are achievable in a single part by AM. How to manage design and represent design knowledge is affected by the no-tooling and sustainable manufacturing way. However, the most influential one is the way how AM enriches attributive and functional information of design solutions. The impact on this category is reflected on the design considerations for manufacturing, assembly and performance, which will be illustrated in sections 2.1, 2.2 and 2.3 respectively. In the end, important notes are given in section 2.4.

2.1 Design considerations for manufacturing

From conventional DFM perspective, DFM rules and practices are well exemplified in Handbook for Product Design for Manufacture [25] and Product Design for Manufacture and Assembly [26]. The extensive efforts on DFM over many years are an indication of the difficulty and pervasiveness of the issues surrounding DFM [14]. DFM requires designers to have a good understanding of the manufacturing constraints imposed by available fabrication methods. Some of these manufacturing constraints are lessened by AM while some are not. The challenges for DFM in AM application are reflected in the following aspects where conventional DFM fails to match the advantages provided by AM.

Firstly, the layer by layer working mechanism and direct fabrication from CAD model, totally expands designers' imagination in part design. Unlike the subtractive and formative processes, this additive process can virtually build parts with any shapes. Prof. Hague's group[27,28,5] focused on studying the differences between AM and injection moulding to analyze the impact on DFM. In the comparison research, DFM requirements for injection moulding such as uniform wall thickness, avoiding sharp corners and minimising weld lines become invalid for AM cases. In their following research [29], geometric and design complexity, part consolidation, customization and multiple assemblies are investigated. The research indicates that traditional part complexity measurement that is based on cost of manufacturing, cost of assembly, and serviceability are challenged by AM due to the fact that the way of calculating manufacturing cost and assembly has totally changed.

Secondly, parts could advantageously be designed from the modular and hybrid point of view, whereby parts are seen as 3-D puzzles with modules. These modules are realized separately and further assembled with the main advantages of possible alternative design and reduced manufacturing difficulties. This kind of hybrid manufacturing method can be divided into two categories. The first one is the combination of different AM technologies like the combination of Stereolithography (SL) and Direct Write (DW) in the area of electronics [30,31]. An example of the fabrication of a magnetic flux sensor using SL and DW is illustrated in Fig. 1. In this process, SL provided substrate/mechanical structure while interconnections were achieved using DW of conductive inks. Researchers have demonstrated similar capabilities with extrusion-based systems, ultrasonic consolidation, SLS, and other technologies as well. The second one is the combination of AM and conventional manufacturing methods such as SLM and CNC machining, and high resolution SL and micro wire electro discharge machining (μEDM) in micro RF relay design [32]. A new DFM system to conduct manufacturability evaluation in case of a subtractive process alone or an additive manufacturing alone or hybrid modular optimization combination is developed in IRCCYN center in France [33].

Thirdly, since materials with AM technologies can be processed at each point or at each layer at a time, the manufacturing of parts with complex material compositions and designed property gradients is enabled. For example, heterogeneous structure can be achieved by differentiating structure density with respect to load conditions.

As shown in Fig. 2 , the 2D cantilever beam is fixed on left side and uniform force is dispersed along the lengthwise. Compared with the homogeneous lattice structure in (a), the optimized structure in (b) has heterogeneous cell space in proportion to load condition where more density is distributed on the cross-section that has higher torque.

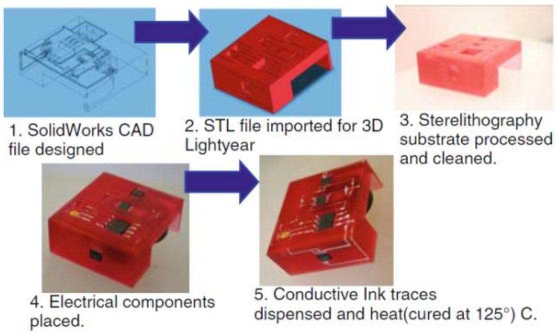
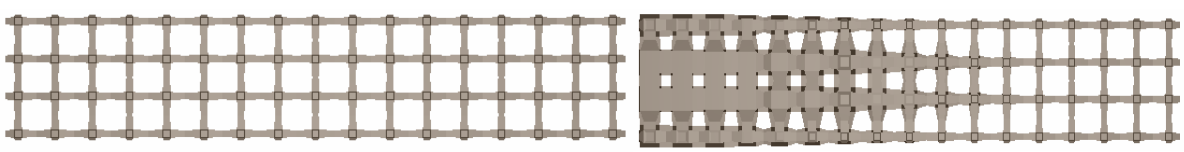


Fig. 1 Fabrication of a magentic flux sensor using SL and DW

Fourthly, AM process enables the fabrication of architecture design of hierarchical complexity across several orders of magnitude in length scale. There are three typical features in reported research which are tailored nano/microstructres, textures added to surfaces of parts and additional cellular materials (materials with voids), including foams, honeycombs, and lattice structures. Lattice structure tends to have geometry variations in two dimensions as is illustrated in Fig. 3. The first dimension is octet-truss unit, the second dimension is pure truss lattice structure or lattice with skin in meso-level. There are potentially many applications where 3D micro-features can benefit the overall function of the macrostructure [34]. one such application involving typical combination of macro feature and micro feature was a swirling flow coaxial phacoemulsifier sleeve with internal micro-vanes [35] as shown in Fig. 4.

Fifthly, the unique process characteristics of AM make it possible to remanufacture and repair with low cost and relative high speed. As shown in Fig. 5 a Ti-6Al-4V bearing housing from a gas turbine engine was repaired by LENS AM process [36]. The bearing seating area was worn off to an out-of-tolerance condition, thus the housing was considered scrap. The LENS process was utilized to build up the worn area, which was followed by final machining to meet tolerance requirements. This housing was successfully repaired, with no measurable distortion, and has completed an evaluation run in a test engine. The repair costs are about 50% of new pricing plus it saves all of the materials that would be required to manufacture a new housing.



(a) (b)

Fig. 2 An example of lattice structure: (a) Homogeneous lattice; (b) Heterogeneous lattice.

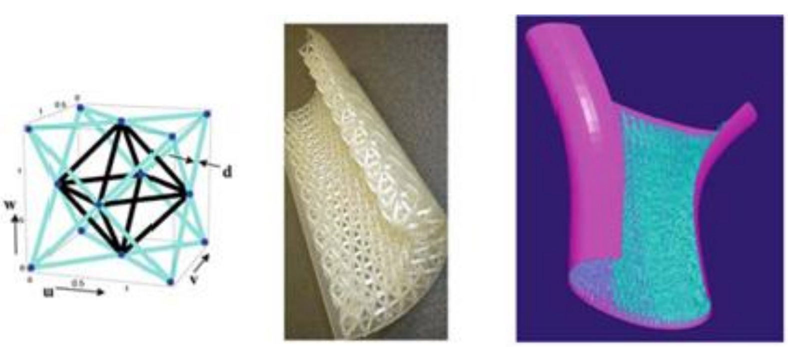
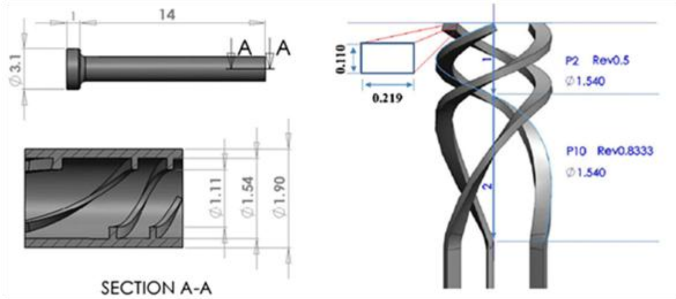


Fig. 3 Octet-truss unit cell and example parts with octet-truss meso-structures[34]



(a) (b)

Fig. 4 3D model of the sleeve with micro-vane: (a) hollow tube and section, (b) microvanes (dimensions in mm) [35]

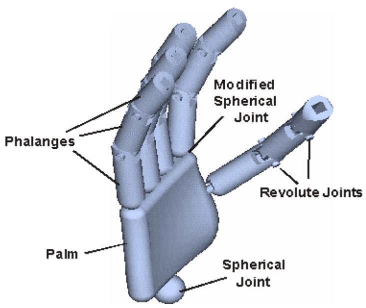
Fig. 5 Low-wattage repair of Ti-6AL-4V bearing housing [36]

2.2 Design considerations for assembly

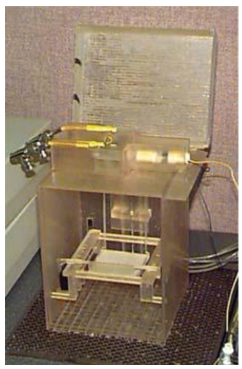
In conventional DFA aspect, two main considerations are often offered to reduce assembly time, cost, and difficulties: minimize the number of parts and eliminate fasteners. Both considerations are translated directly to fewer assembly operations, which is the primary driver for assembly costs [26]. Traditionally, assembly's main function is to join components, formless material and sub-assemblies into a complex product [37]. In contrast with conventional assembly process, AM enables part consolidation in the place where parts used to be fabricated separately due to manufacturing limitations, material differentiation or cost. Manufacturing limitations are lessened by AM (refer to section 2.1), and AM offers a totally different perspective of joining compared to conventional assembly. The challenges for design considerations for assembly in AM processes are discussed in the following section.

Firstly, AM facilitates integrated assembly and embedded components because of layer by layer or point by point characteristics. Typical applications are classified into two groups: operational mechanisms and embedded components. In the operational mechanisms case, even when two or more components must be able to move with respect to one another, AM can build these components fully assembled. For example, the prototype of mechanical components of a four degree of freedom finger of a five-fingered robotic hand (see Fig. 6 (a)) was fabricated by SLS process [38]. To improve the mechanism's performance, the key influential parameter, that is joint clearance, was studied in [39] for this kind of non-assembly mechanism. In the embedded components case, it is often advantageous to embed components into a part to construct a functional prototype to improve systematic performance. These embedded components include small metal parts (bolts, nuts, bushing), electric motors, gears, silicon wafers, printed circuit boards, and strip sensors. A prototype with 11 embedded components was built in a SL-250 machine as depicted in Fig. 6 (b).

Secondly, joining multiple materials together by AM is a feasible assembly method. The use of multiple materials within AM to increase part functionalities has been considered by many researchers in the form of FGMs [40-43]. However, there are many fabrication issues to be addressed in these cases in addition to the dilemma of recycling components fabricated of multiple materials. Functionally Graded Rapid Prototyping (FGRP) is a novel design approach and technological framework enabling the controlled spatial variation of material properties through continuous gradients in functional components [44]. As shown in Fig. 7, the design combined structural, environmental and corporeal performance by adapting its thickness, pattern density, stiffness, flexibility and translucency to load, curvature, and skin-pressured areas respectively. A single continuous surface acting both as structure and as skin was locally modulated to cater for structural support on the one hand, and corporeal performance on the other. Through FGRP, Oxman et al. [45-48] achieved Variable Property Design Fabrication and developed a physical prototype of Variable-Property 3D printer.



(a)



(b)

Fig. 6 Example of AM facilitated assembly integration and embedded components: (a) a four degree of freedom finger of a five-fingered robotic hand; (b) a model built in a SLA-250 machine with 11 embedded components.

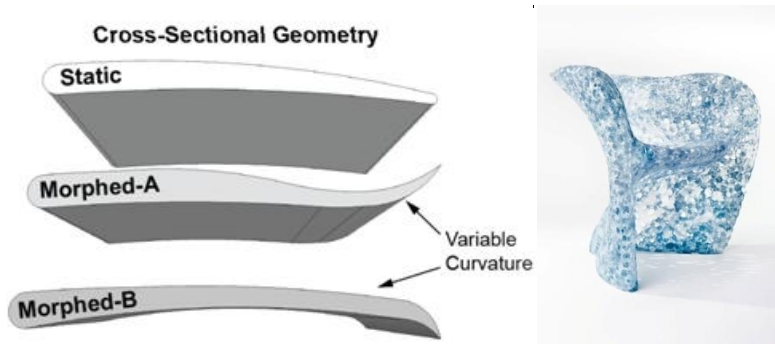
Fig. 7 A conceptual chair made by FGRP with variable stiffness and elasticity [44].

2.3 Design considerations for performance

The impact of AM capabilities on DTM is never limited to DFM and DFA. AM shows its uniqueness in building a part with extreme complex geometric structure without increasing manufacturing difficulty. Traditionally, product with simple geometry is desired despite of sacrificing its function or performance. In order to improve structural performance, multifunctional and flexible structures are designed for AM. The ability of AM to produce highly flexible and functionally integrated parts fosters the idea to create smart parts that quickly adapt and response to the operation environment. This type of parts are also called morphing structures. For instance, by varying the cross-sectional shape, a morphing wing could adapt to respective flight phases and high-speed phenomena through providing the laminar flow of air over the dynamics and control surfaces. Therefore, the buoyancy force can be varied and vicious drag can immensely be reduced. One possible morphing working mechanism is shown in Fig. 8 (a). This effect can be realized more efficiently with less turbulence by the modulization of wing geometry. As illustrated in Fig. 8 (b), the cellular chair serves the functions of aesthetics and support [49].

Apart from achieving multifunctional and flexible structure, AM enabled design could be optimized for other better performance, such as weight reduction, better heat dispersion, and less stress concentration by means of heterogeneous structures. Heterogeneous structures can be achieved in two levels. The first one is material level. Besides FGMs, another possible way is to mix different cell units of the same material within the same design domain meanwhile the drawbacks of computational power requirement and dilemma of recycling of FGMs are avoided [4]. The second one is at meso structure or macro structure level. This type of heterogeneousness can be achieved by topology optimization and cellular structures. A piece of cockpit plane for the maintenance of wiring and it is redesigned to fulfill the objectives of weight reduction [50] (see Fig. 9).

Actually, from the perspective of life-cycle product management, AM enables the real integration of design and manufacturing [51]. For the purpose of functionality and manufacturability integration, the structural



(a) (b)

Fig. 8 Examples of flexible structure and a multifunctional part: (a) morphing wing working mechanism; (b) cellular chair

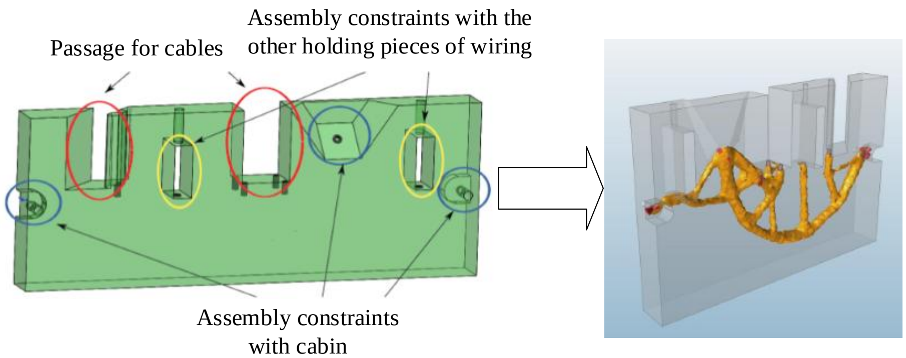


Fig. 9 The redesign of a cockpit plane for weight reduction [50]

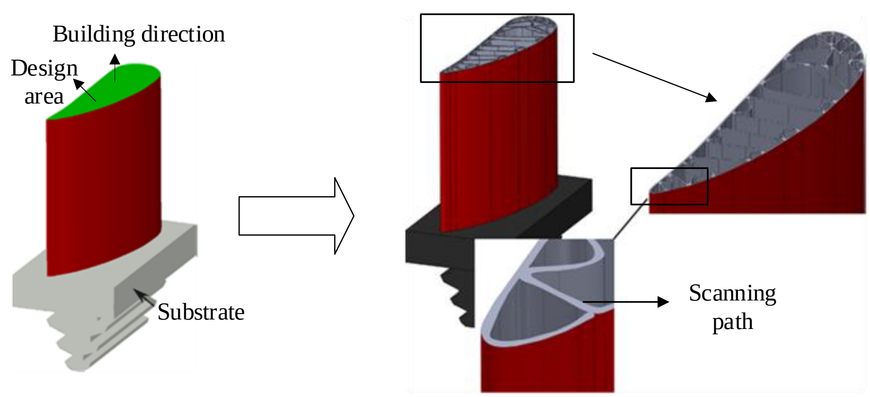


Fig. 10 The redesign of an engine blade based on scanning path [52].

optimization of a blade [52] by taking into consideration manufacturing path and load condition is illustrated in Fig. 10.

2.4 Discussions

Design considerations for manufacturing, for assembly, and for performance are correlated rather than being independent. In order to study the relationship of these three aspects and better understand how to take full advantage of AM in design, objectives of DFX (refers to DFM, DFA, DFMA, and DFD in this report) are initially summarized as: the ease of manufacturing, the ease of assembly, the ease of repair, maintenance, reuse and recycle, manufacture cost reduction, assembly cost reduction, and disassembly effort reduction. Furthermore, guidelines for conventional DFX are grouped and represented in a formatted language:

1) Design simply: simplify structures complying with functional requirements;
2) Minimize part count;
3) Integrate parts;
4) Separate working components into modular sub-assemblies;
5) Minimize material types in an assembly;
6) Standardize components;
7) Create multifunctional parts;
8) Design for the ease of fabrication;
9) Design for the ease of assembly: positioning, handling, joining and access;
10) Avoid using laminates;
11) Avoid surface demands on components;
12) Avoid secondary operations;
13) Eliminate adjustments;
14) Use ferromagnetic materials;

As shown in Fig. 11, items 1, 2, and 6 are the commonalities among all the four methods and each item has its own focuses. It is important to find that item 8 and 9 are located on the periphery, because there is a trade-off between DFM and DFA in terms of design complexity and manufacturing constraints. However, due to the capability of AM, the trade-off becomes deactivated.

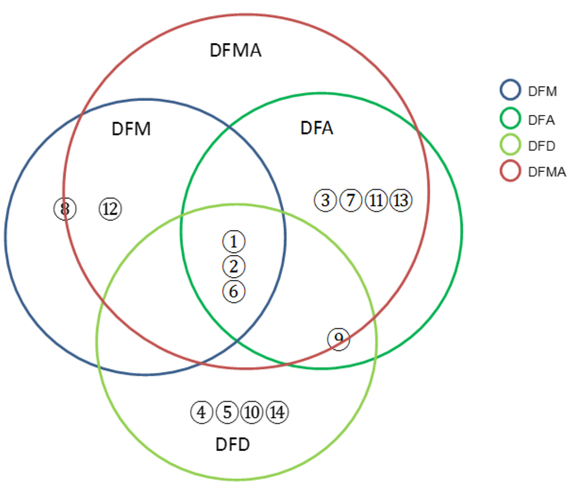


Fig. 11 Relationship between DFM, DFA, DFD, and DFMA.

3 AM related design methods

According to the review of AM's impact on conventional DTM, it is imperative to note that conventional DTM is not qualified to embrace these new opportunities brought by AM. Meanwhile, AM process has some limitations and drawbacks such as building time, surface roughness and recycling dilemma, which should be solidly incorporated into design considerations. In this section, research on how to take full advantage of AM is summarized. Generally, these methods can be divided as general design guidelines, modified conventional DTM for AM, and Design for Additive Manufacturing.

3.1 General design guidelines

The first method for guiding design was to follow a general set of rules or guidelines. These rules generally are not quantitative in nature and require a human to interpret and apply to each specific and unique case. Whilst this is much better than just blindly starting each design from scratch, it does require some skill and knowledge on the part of the designer to correctly interpret and apply the rules, which is not enough for taking full advantage of AM capabilities.

Realizing the opportunities brought by AM, Becker et al. [53] introduced some major design guidelines for rapid manufacturing and apply these guidelines to a case study of a mix device, as shown in Fig. 12. The optimized part has advantages in reduced part count, less assembly effort and advanced functionality. The proposed design guidelines are listed below:

- Use the advantages that are included in RM processes.
- Do not build the same parts designed for conventional manufacturing processes.
- Do not consider traditional mechanical design principles.
- Reduce the number of parts in the assembly by intelligent integration of functions.
- Check if there are bionic examples to fit your tasks as these can give a hint towards better design solutions.
- Feel free to use freeform design; they are no longer difficult to produce.

- Optimize your design towards highest strength and lowest weight.
- Use undercut and hollow structures if they are useful.
- Do not think about tooling because they are no longer needed.

Since there is no tooling and semi-finished part needed, parts can be created directly based on required functionalities and geometry [53]. The design process of a robot gripper was given in [53] to illustrate the general design process. However, the proposed design process is only suitable for a design whose initial CAD data is known beforehand. The second problem is that the only advantage of AM embraced by this method is no tooling while other advantages of AM is not fully reflected in the design process.

Similarly, a lot of reported research on design rules partially overlaps with design guidelines. Design guidelines focus on a more general discipline where designers are encouraged to make a better design by taking advantages of AM. For example, through the comparison of injection moulding and SLS for medium volume plastic part production in terms of geometric possibilities and cost, major design guidelines for AM was given by Atzeni et al. [54]. In contrast, design rules deal with a more specific aspect of identifying the limitations of AM, serving as design code. Abundant research can be found in this area [55,15,56-60]. Research on design rules can be divided into two groups: experimental method, for example benchmark study, and systematic method. The former one is represented by the research of Daniel [15]. In his research, the geometric limitations of Selected Laser Melting (SLM) were evaluated through a quantitative cyclic experimental methodology. Part orientation, fundamental geometries and compound design features were explored to generate the design rules for the SLM process. The experimental method about of testing geometric limitations can be modified for other machines; however, since the proposed design rules are based on a SLM system, inevitably, some design rules like the minimum wall thickness which are dependent on the process and the SLM machines, are biased. A more effective way to verify design rules is to build benchmark. In benchmark tests [58-60], mechanical properties such as tensile and compressive strengths, hardness, impact strength, heat resistance, surface roughness, geometric and dimensional accuracy, manufacturing speed, and material costs were compared for different types of AM process. The second one is represented by Zimmer's group [55]. The group was working on a project named "Direct Manufacturing Design Rules 2.0" where function independent design rules were studied for Laser Sintering, Laser Melting and Fused Deposition Modeling AM processes. Within the suggested research flow, geometric elements are firstly defined as basic elements, element transitions, and aggregated structures. Then, after studying the attribute value, boundary conditions of these groups, design rules are obtained. Design rules in systematic method was also reported by Popsecu for Rapid Prototyping (RP) [56] and Kruf et al. for RM [57].

Design guidelines and design rules provide a feasible way to aid designers to design effectively in applying AM technologies; however, this kind of case study orientated guidelines are only suitable for avoiding the restrictions of conventional design rather than providing how to take full use of AM. It is important to note that most of the design guidelines emphasize on how to take advantage of AM capabilities while the unprecedented limitations are rarely studied. One of such work studying the limitations of AM was done by Atzeni et al. [54]:

- support design and removal, limited to some techniques;
- lack of dimensional accuracy and close tolerances;
- stairstepping appearance and poor surface finish;

- minimum wall thickness; mechanical, thermal and electrical properties of currently available materials; and
- in case of large size components RM build time is still quite long compared to Injection Moulding for mass production purpose.

3.2 Modified conventional DTM for AM

Adopting a precise and consistent design methodology to design a product is always suggested [61]. Boyard and Rivette et al. [62] managed to put forward a modified DFMA methodology to improve the design process of AM related design. This design method consists of five steps shown in Fig. 13 (a): functional specifications, conceptual design, architectural design, detailed design, and implementation. It is characterized by the feature that DFA and DFM works in parallel simultaneously other than sequentially. This feature is enabled by a modular and modifiable function graph in conceptual design phase where each function is represented by a sphere node and these nodes are linked by segments to indicate direct relationship of functions and spatial locations. Once these nodes and links are established, functional sets are determined by the criteria oriented from DFA against which each part should be examined as it is added to the product during assembly [26]. A function graph of sets was proposed to model a product and each set represents a part and different sets are connected by dotted lines (see Fig. 13 (b)).

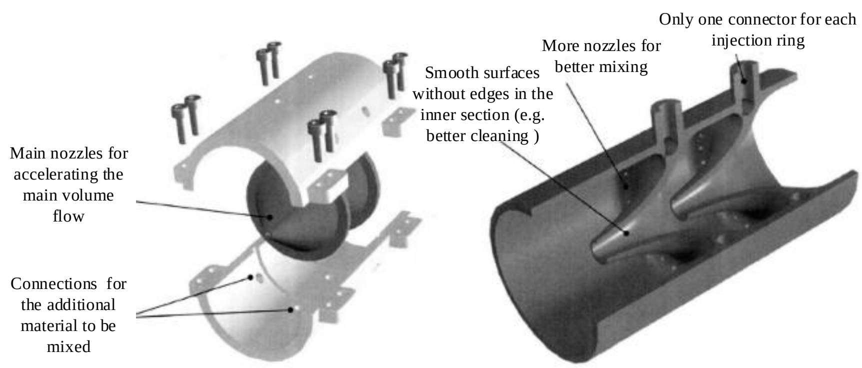


Fig. 12 An optimized mix device using the design guidelines proposed in [53].

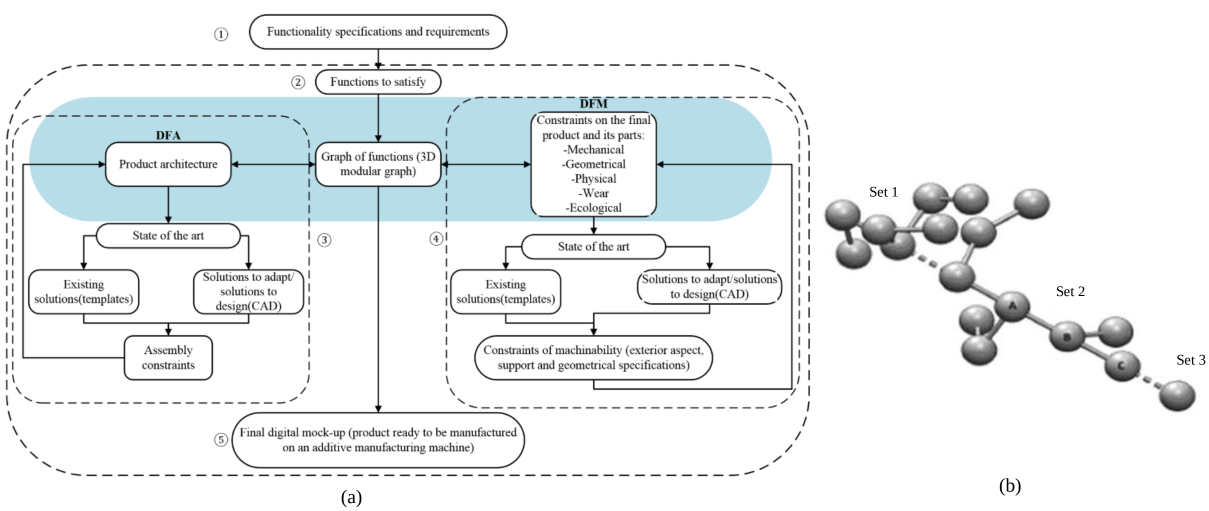


Fig. 13 Design methodology proposed by Boyard and Rivette [62]: (a) the modified DFMA method; (b) function graph.

This kind of function graph allows users to spatially recognize functions and functional relationship. However, whether it is reasonable to link function A and function B is not given. For example, function A and function B both belong to set Ω by proposed criteria while the relationship between A and B is not defined. This proposed design methodology facilitates the idea of considering DFA and DFM simultaneously in AM design process while it is not well developed for complete AM design innovation. For instance, it does not deal with product containing inner relative movement and hierarchical complexity.

In order to develop a design methodology specially for AM, Rodrigue [63] asserted that DFA and DFM were the only possible design methodologies related to AM. In the case of AM, geometry constraints and assembly difficulties were proven to be less important. To optimize the product with respect to assembly and manufacturing, DFA and DFM were performed to meet the initial user's requirements. Then a redesign methodology was proposed to optimize product for preventing failure and the respect of user requirements. Prevention of failure was based on FMECA (Failure Modes, Effect and Criticality Analysis) which was derived from FMEA. It aims to increase the reliability to meet the specifications. Compliance with user requirements aims to meet the design constraints with minimum compromise. Finally, the optimization is confronted to decide the structure and shape of the final product, as shown in Fig. 14. This method emphasizes more on design reliability while how to meet user requirements are not clearly discussed.

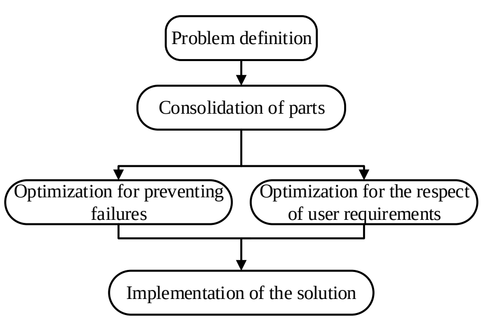


Fig. 14 Redesign methodology for AM [63].

3.3 Design for Additive Manufacturing

In the early stage, there are some initial concepts of Design for Rapid Manufacturing (DFRM) reported by some researchers such as Atzeni et al. [54]; however, the development in this area remains as a part of DFM, which makes little contribution for generating a comprehensive design method in methodology level. Frankly, DFAM can be considered as the evolved idea of DFRM that benefits the designers to avoid considering the constraints in conventional DTM to some extent. In this section, emphasis is placed on summarizing what kind of design methods is available for AM. There are numerous researches on DFAM in the past decade and in general, they can be grouped in two categories. The first one sticks to the scope of AM enabled structure optimization design method and the second one focuses on DFAM methodologies.

Generally, structure optimization methods are more specific with concrete objectives. AM related structure design optimization methods can be classified by different objectives, such as optimization for stiffness and strength [64-67], compliance [68,69], and manufacturability [33]. In addition, structural optimization methods has spread to other disciplines such as dynamic [70,71], thermal [72-74] and bio-medic field [75-77]. However, most of these structure optimization methods focus on how to obtain optimal structures according to specific objectives other than how to model the design process where AM capabilities can be better involved.

In contrast, design methodologies are comprehensive and systematic design frameworks. Recognising the drawbacks of the difficulty in determining the real optimized characteristics for a given AM process from an initial CAD model which is designed for traditional fabrication method, Ponche et al. [50] proposed a global approach aiming at defining part shapes subjected to the manufacturing process and functional requirements. In their research functional specifications and AM process characteristics were directly combined at the early stage. This is because the choice of manufacturing direction and manufacturing trajectories as well as manufacturing volume, microstructure[78], geometry [79], and manufacturing time [80] are the keys to a global DFAM [50]. Corresponding to the global DFMA approach, a structured design methodology was suggested. The first step is the delimitation of geometric dimensions in relation to the dimensional characteristics of AM process. The second step is the dimensional and geometric fulfillment with respect to functional specifications and process characteristics. The last step is to fulfill physical and kinematic requirements. In their following researches, the influence of manufacturing path on structure design is much emphasized [52] and the balance between functional requirements and manufacturing constraints is studied [81]. Manufacturing path topology is determined from manufacturing constraints and initial part geometry.

After identifying the specific manufacturing capabilities as well as the manufacturing constraints of laser-based or EBM-based AM process in terms of accessibility constraints, frequent acceleration and deceleration stage, heat dissipation, disability to build closed hollow volume, a general four-step design process was proposed by Vayre et al. [82,83]: analyze the specifications, initial shape, parametric optimization and validation of manufacturability. The design process is verified by the redesign of a square bracket part (see Fig. 15). Inevitably, this design process is way too generic on how to form initial shape and do parametric optimization. Besides, the process knowledge like the need for assembly is underestimated.

Undeniably, these two kinds of design methodologies enhance the concept of combining functional requirements and manufacturing constraints in an AM related design and the innovative idea of functional surfaces and functional volume solidifies the purpose of maximizing design freedom enabled by AM. However, the problem is that the aspect of assembly and structure performance is not covered, which may result in a partially optimized design. Also, the ability to do function integration is rarely reported.

In the area of AM enabled structure optimization, only design methods are reviewed here rather than optimization theory. Most of the researches focus on specific dedicated structures such as lattice structure. A more comprehensive DFAM system is proposed by Rosen [34] consisting of part and specification modeling, process planning, and manufacturing simulation (see Fig. 16). In the DFAM system, cellular structure design parameters optimization and Manufacturing ELement (MEL) method for process planning are the

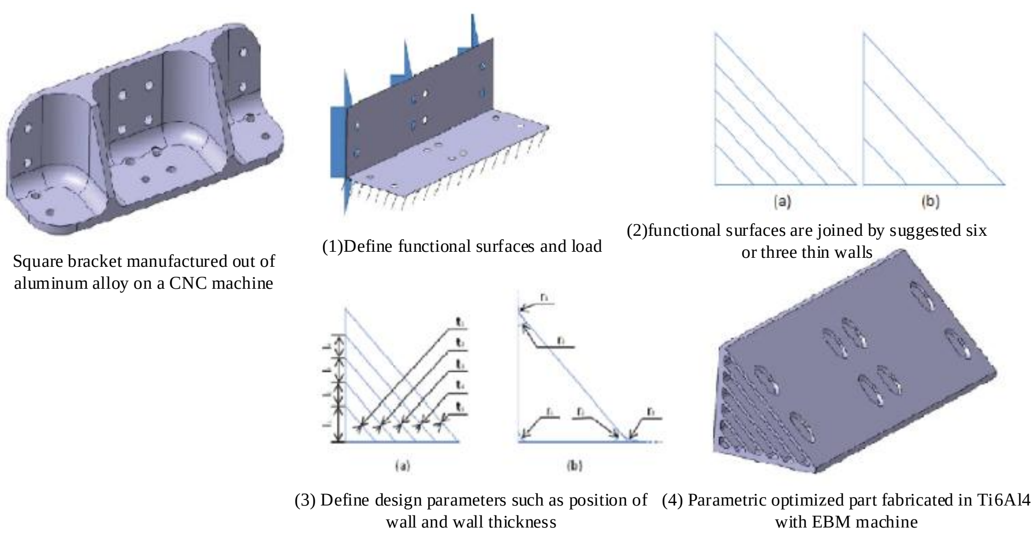


Fig. 15 The redesign process of a square bracket modified from [82]

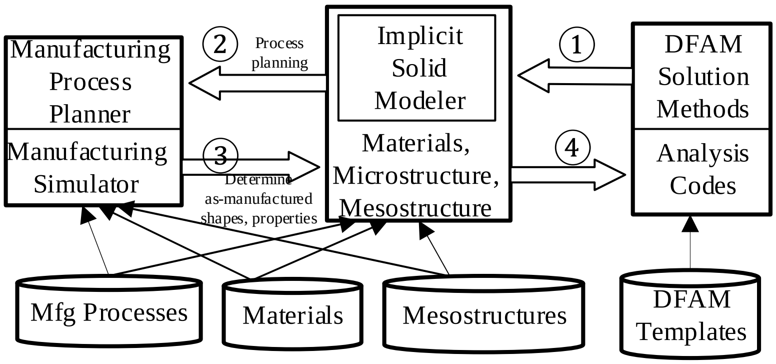


Fig. 16 DFMA system and overall methods [84]

keys to take advantages of AM uniqueness. In his following research [84], a sequential two-stage method for multifunctional topology application was proposed. The first stage is to develop a preliminary topology with structural performance that meets objectives as closely as possible while remaining insensitive to bounded adjustment in topology itself. The second stage is to modify the previous topology to improve the performance in the secondary domain such as conjugate heat transfer or vibration absorption. However, the proposed DFAM system focuses on the downstream manufacturing process and the design environment such as CAD software and simulation software. This system has a basic assumption that cellular structures are the reprehensive architectures which can take full advantages of AM capabilities. However, the design freedom enabled by AM is not limited to cellular structures.

Inspired by the work of Rosen, Tang et. al [85] developed a multilevel design method where both topology optimization in macro level and lattice structure design in meso level are adapted sequentially. As shown in Fig. 17, CAD models generated from CMM or CT scan are also regarded as the initial input; design requirements and manufacturability serve as multi-objectives and constraints respectively. This multi-level design method makes a step further to employ AM to make a better design

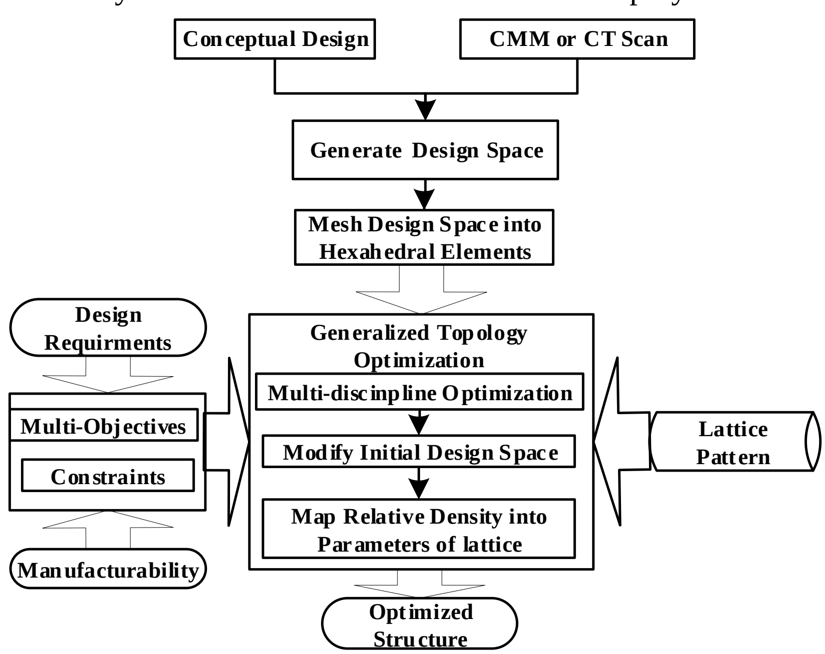


Fig. 17 A multi-level design method

while topology optimization and lattice structure are specific structure design methods and they are only a part of various optimization methods. Another aspect worth mentioning is that the proposed method focuses on the design of a single part. To fundamentally maximize the potential of AM capabilities in design, a more theoretical and general design method should be guaranteed.

In order to ease the designers' work of DFAM, a DFAM method based on design features was proposed to decide the feasibility and suggest appropriate design features to be added into a product design [86]. AM feasibility validation, AM concept profile selection, and database of AM relevant design features are the three key points in realizing this method. For AM feasibility validation, a weighting and rating technique is used to evaluate the feasibility of AM process. Then, AM concept profile is selected based on design taxonomies of user-fit requirement, functionality improvement, consolidation requirement, aesthetics and form requirement. Admittedly, the design feature database can aid design beginners to make a better design; nevertheless, whether the designed features are reasonable and how much effort can be saved for the proposed design system is in doubt. Another deficit is how they validate the feasibility of AM. The validation method is based on a user interactive interface of merely asking information about the product volume and geometric accuracy requirements other than geometric limitations.

3.4 Summarization

AM processes enable the design freedom in the aspects of shape complexity, material complexity, hierarchical complexity and functional complexity as well as process opportunities in the aspects of manufacturing and assembly. The significantly expanded design freedom and process opportunities challenge conventional DTM in not being able to take advantage of these new capabilities. Although the idea of providing design guidelines, modifying conventional DTM, and DFAM can further designers' understanding of how to better the employment of AM in a design, there are still some problems that are not fully discovered.

(1) The difficulty in determining the real optimized characteristics for a given AM process from an initial CAD model which is designed for a traditional fabrication method, has not raised enough attention.

(2) The perspective of DFAM adapting topology optimization and cellular structure furthers a step to make a better design, while these specific structure optimization methods impede the possibility of maximizing the potential of employing AM capabilities. Most of these design methods are only applicable in downstream design activities, i.e. detailed design phase.

(3) The concept of combining functional requirements and manufacturing constraints into an AM related design, and the innovative idea of functional surfaces and functional volumes initialize the purpose of maximizing design freedom enabled by AM. However, how to match functional requirements and manufacturing constraints with physical attributes is rarely involved.

(4) The aspect of manufacturability and assemblability improvement is rarely covered in AM related design methods, which tends to generate a partially optimized design.

(5) Most of the available design methodologies are semantic representation which is difficult to be implemented and to keep design flow consistent.

4 Discussion

Based on the above research reviewed, it is indicated that there is a need for a new design methodology to fully take the advantages of AM capabilities. However, this intricate issue cannot be addressed with ease. One possible and reasonable way is to focus on the downstream design stage first to integrate process knowledge and structure optimization to reduce part count and improve the potential performance such as lighter weight and better mechanical properties subject to user requirements. The main idea of this step is to verify the feasibility of AM enabled part consolidation which employs almost all the design freedom of AM. This design method is corresponding to problem (2), (3), and (4) in the section 3.4, which means that this method has only partially overcome the drawbacks of existing design methods for AM.

Based on the initial input of this design model, part process can be divided into two main steps (the highlighted rectangular). The first step is to analyze the initial CAD model and perform part consolidation in functional level according to functional requirements and performance requirements. This step is defined as function integration as shown in Fig. 18. In the second step, structure optimization methods are applied to newly generated design space to achieve better performance such as lighter weight, better heat dispatch or dynamic properties under the requirements of performance. The above two steps should also comply with the process constraints of manufacturing, assembly, and standardization. After that, design solutions are verified. If there is no design solution, design flow goes back to function integration and necessary modifications should be done in this step. If design solutions are found, output the design solutions and the original part is redesigned with less part count and better performance.

5 Conclusions and future research

In this literature review, the impact of AM on conventional DTM is analyzed in the perspectives of design considerations for manufacturing, for assembly, and for performance. In order to meet with these new challenges, reported AM related design methods are summarized. Through the thorough review, current design methods can be divided into three categories: general design guidelines, modified conventional DTM for AM, and DFAM. Although some progress has been made future research should be done in the following areas:

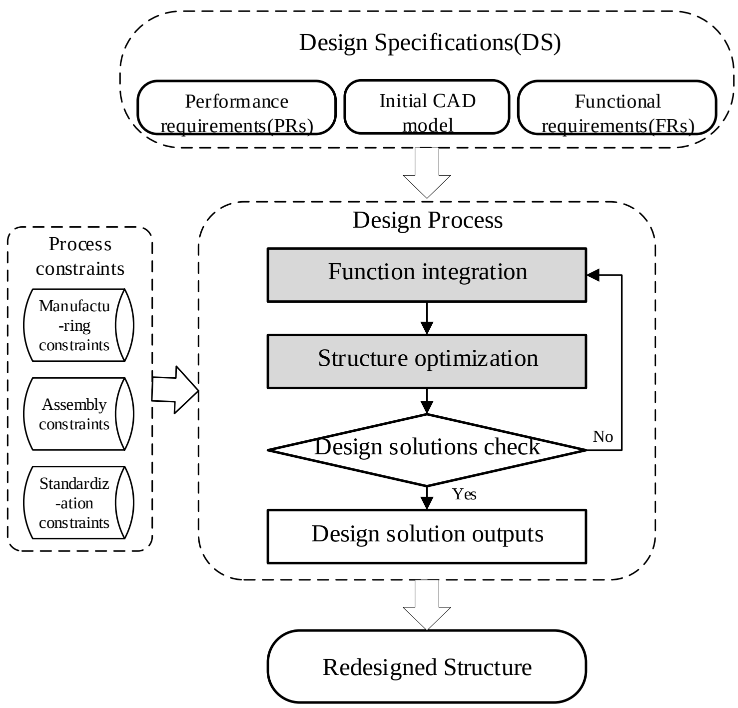


Fig. 18 Proposed AM enabled design method

(1) Develop a generic design framework which initializes design from the perspective of functionality achievement. As it is mentioned in the literature review, most of the current research work focuses on optimizing the existing model designed by traditional design methods which are largely limited by traditional manufacturing methods.
(2) Develop a method to better synthesize functional requirements and process knowledge simultaneously. Although AM has alleviated the need for joining operation, assembly cannot be avoided due to motion and disassembly requirements. Moreover, DFM should not be limited to AM because traditional fabrication processes are still reasonable in some cases.
(3) Develop an analytic model for design rationalization and multifunctional optimization. Most of the available design methodologies are semantic representation which is difficult to be implemented and to keep design flow consistent; thus, a mathematical model for governing design process is necessary.

Acknowledgements Financial support from the National Sciences and Engineering Research Council of Canada Discovery Grant RGPIN 436055-2013 and McGill Engineering Doctoral Award (MEDA) is acknowledged with gratitude.

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