Sustainable Design for Additive Manufacturing Through Functionality Integration and Part Consolidation

Yunlong Tang, Sheng Yang and Yaoyao Fiona Zhao

Abstract Additive Manufacturing (AM) is a type of material joining process whereby parts can be directly fabricated from its 3D model by adding materials typically in a layer by layer fashion. Compared to conventional manufacturing techniques, AM has some unique capabilities which bring significant design freedom for designers. Some of this design freedom is manifested in the innovative design of lattice structure to achieve multifunction with reduced weight and consolidated component designed with reduced part count and improved performances. A new type of design philosophy for AM is emerging that is to achieve integrated functions and part consolidation, which plays a significant role in sustainable design. This chapter discusses this new design philosophy with a thorough review of lattice structure design and optimization methods, design for AM methods, and other related new design methods. It presents a general design framework to support sustainable design for AM via functionality integration and part consolidation. This proposed general design methodology supports the design that has less part counts and less material but without compromising its functionality. A case study is given at the end of the chapter to illustrate and validate the proposed design methodology. The result of this case study shows that the environmental impact of a product's manufacturing process can be reduced by redesigning the existing product based on the proposed design methodology. Moreover, compared to its original design, the redesigned product also has a lower part count. Generally, this case study implies that design freedom enabled by AM is an indispensable factor which needs to be considered during the environmental impact analysis of products fabricated by AM processes.

Keywords Additive manufacturing · Environmental impacts · Functionality integration · Life cycle assessment · Parts consolidation · ReCiPe midpoints indicator

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1 Introduction

Additive Manufacturing (AM) is a new emerging technology that joints material typically in a layer by layer fashion. It has been increasingly used in the new product developing spanning conceptual design, functional design, and tooling. AM is also referred to as 3D printing, rapid prototyping, solid freeform fabrication, and direct manufacturing. It has shown great promise in applications to medical implants and the aerospace and automobile industries (Hopkinson et al. 2006; Gibson et al. 2010; Murr et al. 2010). A variety of raw materials can be used in AM processes including metal, plastic, ceramic, sand, and composites. AM can build a part directly from a digital representation without tooling and fixtures. Although AM is inherently suited for making products with high complexity in small batches, it has shown great capability to accelerate mass production by making tools and dies used in large volume manufacturing. It can also accelerate the production of selected parts by combining multiple parts into one.

The AM fabrication process has many unique characteristics that are very different from conventional manufacturing and proper selection of the process parameters significantly affects the product's quality. Thus, planning decisions to select an appropriate AM process and its parameters for specific application requirements and design are rather involved. Extensive research work has been done to analyze the influence of AM process parameters on end product quality such as surface finish, dimensional accuracy, and mechanical properties (Singhal et al. 2009; Byun and Lee 2006; Delgado and Ciurana 2012). With proper fabrication parameters, functional products with high complexity, multi-functions, reduced part count, and high added value can be produced without significant increase of manufacturing cost. Thus, this process is widely described as a "clean" or "green" process because only the exact amount of material to build the functional parts is needed (Bourhis et al. 2014). However, such claim needs to be assessed quantitatively with the consideration of the entire life cycle and only very limited research has been done on this topic. Most reported research in this area has been aimed at:

1. Developing general process models and environmental evaluation methods (Luo et al. 1999; Le Bourhis et al. 2013)
2. Understanding the environmental impact of specific AM processes (Kellens et al. 2011, 2012)
3. Measuring life cycle inventory data of specific AM processes (Sreenivasan et al. 2010; Xu et al. 2014)
4. Comparing the environmental impacts of different AM processes and conventional manufacturing processes (Mani et al. 2014; Morrow et al. 2007; Yoon et al. 2014; Faludi et al. 2015)

Most research was conducted within the established framework of Life Cycle Assessment (LCA), through which quantitative environmental impact data can be obtained based on new unit AM process models, assessment boundaries, and cut-offs. When using this method, a static LCA analysis is performed after a product is manufactured, by which time the environmental impacts have already been generated. LCA tools are typically not integrated with other design analysis and process optimization methods. Most comparisons between the environmental impact of AM processes and conventional manufacturing process have so far been done for the same product design (Mani et al. 2014; Morrow et al. 2007; Yoon et al. 2014; Faludi et al. 2015). The use of the same conventional manufacturing product design as input for an LCA study is to a certain extent misleading because the extensive research on Design for Manufacturing (DFM) over the past several decades has established valid and often standard geometric features for product design to maximize manufacturing efficiency and minimize manufacturing cost. Such DFM methods and guidelines do not apply to AM (Yang and Zhao 2015), thereby making the sustainability analysis results of AM technology look less appealing. Deeper analysis reveals that AM technologies provide designers with unique and extensive freedom to optimize further the design to be more environmental friendly without compromising its functional performance. For example, structural optimization methods can be applied to reduce structural weight significantly, which may decrease energy and material consumption during product fabrication. Recent studies show that the fabrication of the optimized product allows one to "cut material consumption by 75 % and CO_2 emission by 40 %" (www.3Ders.org 2013). Thus, it is unfair to study the sustainability of AM processes based on the same product design. The design freedom of AM needs to be considered in the sustainability analysis and evaluation. Furthermore, the design freedom provided by AM enables mass customization within the industry. Another advantage of AM processes is the ease of embedding unique product features to achieve targeted functionalities. Short design to fabrication turnover is another benefit of AM processes that enables quick redesign to improve a product's functional performance as well as its sustainability. It is known that the design has the most influence on the sustainability of a product in its entire life cycle (Seliger et al. 2011).

Thus, this chapter first gives a thorough review of design methods for AM including lattice structure design and its optimization methods, design for AM methods, and other related new design methods. It then presents a general design framework to support sustainable design for AM via functionality integration and part consolidation. This general framework mainly consists of four stages. In the first stage, initial functional design has been done to determine the physical entities based on the input functional specifications. In the second design stages, AM-enabled design optimization methods can be applied to minimize the environmental impact of products manufacturing process based on the pre-feedback of environmental impact evaluation model. Then the optimized FVs are further refined and divided into several different parts based on assembly requirements for its related parts. Some assembly features can be added. Finally, the sustainability evaluation model can be used to estimate the sustainability of design solutions for a given AM process. Based on the result of evaluation, the optimized design solution and its environmental impact during the manufacturing phase can be output. A case study is presented to validate the proposed design framework.

2 AM Enabled Design Methods

It is widely acknowledged that design for environment or sustainability should satisfy all the function requirements and performance requirements in the first place. To facilitate a general design methodology for sustainability in the context of AM, there is a strong need to understand how to satisfy these function requirements and performance requirements in the design process with a priority of sustainability consideration. With AM evolving from rapid prototyping to rapid manufacturing, this novel technology is being widely applied in industry to fabricate functional parts. However, how to effectively employ the design freedom enabled by AM and comply with inherent manufacturing constraints remains undeveloped. To make a breakthrough, the impact of AM on conventional design theory and methodology (DTM) is briefly summarized in Sect. 2.1. With the awareness of this impact, ongoing research on design for AM draws much attention and is discussed in Sect. 2.2. To finalize how to design for sustainability within the scope of AM, current AM-related design research on sustainability is discussed in Sect. 2.3.

2.1 *Impact of AM on Conventional DTM*

It is asserted that the most useful and practical theories and methodologies are characterized by mathematic foundation, concrete objectives, or explicit processes (Tomiyama et al. 2009). Therefore, this chapter narrows the scope into analyzing the very DTM which matches these characteristics. According to the classification method of DTM proposed by Tomiyama (Tomiyama 2006) based on the General Design Theory (GDT) (Reich 1995), representative design methodologies such as Axiomatic Design (Suh 1990), Systematic design method (Pahl et al. 2007), Design for X (DFX, referring to DFM, DFA, DFMA, and DFD in this chapter), Adaptable Design (Gu et al. 2004), Characteristics-Properties Modeling (CPM) (Weber 2005), and Contact and Channel Model (C&CM) (Albers et al. 2003) 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 "DTM to generate a design solution" and "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 methods. However, most influential is the way 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. For the limitation of content, more information in this section can be found in the authors' review paper (Yang and Zhao 2015).

2.1.1 Design Considerations for Manufacturing

For any functional product, one of the critical steps in the design process is to check manufacturability. Additive manufacturing as a manufacturing process should also follow this procedure because AM still exerts manufacturing constraints on design. Typical manufacturing constraints could be available materials, geometric limitations [such as minimum wall thickness and minimum clearance (Thomas 2010)], dimensional accuracy (Regenfuss et al. 2007) and surface roughness, support design and removal for some techniques such as Selective Laser Sintering (SLS), low mechanical properties [for example Material Jetting process (Wohlers 2010)], building time for large size components, and material recycling [i.e., FGMs (Watts and Hague 2006)]. For conventional manufacturing processes such as machining, forging, injection molding, and so on, DFM rules and practices have already been well exemplified in Handbook for Product Design for Manufacture (Bralia 1986) and Product Design for Manufacture and Assembly (Boothroyd et al. 2002). In contrast, such design rules for manufacturing consideration have not been established yet for AM. The reason may be attributed to a lack of understanding of the physical principles of powder metallurgy and the diversity of AM processes. DFM requires designers to have a good understanding of the manufacturing constraints imposed by available fabrication methods. In this part, the main goal is to illustrate the incompetence of conventional DFM instead of proposing design for AM rules. The challenges for DFM in AM application are reflected in the following aspects:

1. Layer by layer working mechanism and joining material from CAD model data without tooling. This new working principle totally expands designers' imagination in part design. Unlike the subtractive and formative processes, this additive process can virtually build parts in any shapes.
2. Hybrid manufacturing. Parts could advantageously be designed from the modular and hybrid point of view, whereby parts are seen as 3D puzzles with modules. This kind of hybrid manufacturing method can be divided into two categories. The first is the combination of different AM technologies such as the combination of stereolithography (SL) and direct write (DW) in the area of electronics (Perez and Williams 2013; Lopes et al. 2012). The second is the combination of AM and conventional manufacturing methods such as selected laser melting (SLM) and CNC machining.
3. Complex material composition in a controlled manner. Because 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.
4. Architecture with hierarchical complexity. The 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.

5. Repair and remanufacture scenario. The unique process characteristics of AM make it possible to remanufacture and repair with low cost and relative high speed.

According to the above five main challenges on DFM rules, several resultant rules should be considered. The first rule is that when considering hybrid manufacturing, for example, CNC machining and SLM, the DFM rules of CNC machining should automatically be considered, such as tool accessibility. The second rule is that, although AM facilitates multiple material deposition, how to find the material combination and how to avoid stress singularity at the interface is critical. The third rule is that cellular structure sometimes could increase manufacturing difficulty because it is difficult to remove the support structure. The fourth rule is that repair and remanufacture is different from the manufacturing process; in such a case, a new set of rules is necessary.

2.1.2 Design Considerations for Assembly

Most products are comprised of multiple parts, which means that assembly considerations are important. From the 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 (Boothroyd et al. 2002). Traditionally, assembly's main function is to join components, formless material, and sub-assemblies into a complex product (Andreasen et al. 1983). In contrast with conventional assembly processes, AM enables part consolidation in the place where parts used to be fabricated separately because of manufacturing limitations, material differentiation, or cost. Manufacturing limitations are lessened by AM 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:

1. Integrated assembly and embedded components. Layer by layer or point by point characteristics make it possible to realize integrated assembly and embedded components. Typical applications are classified into two groups: operational mechanisms (Mavroidis et al. 2001) 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. 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 (i.e., bolts), electric motors, gears, silicon wafers, printed circuit boards, and strip sensors.

2. A special assembly method. 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 FGM. However, there are many fabrication issues to be addressed in these cases in addition to the dilemma of recycling components fabricated from 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 (Oxman et al. 2012).

2.1.3 Design Considerations for Performance

With AM eliminating much of the manufacturing constraints and assembly needs, designers are partially free from the constraints of design for manufacture and assembly (DFMA), which means that design for performance (DFP) turns into reality. Traditionally, a product with simple geometry is desirable to avoid sacrificing its function or performance because manufacturing cost and difficulty normally increase as structure complexity increases. However, this rule does not fit AM any more. The manufacturing cost and difficulty when using AM is not overly related to structure complexity.

Performance in this chapter is a general term which embraces functional performance and complementary performance. Functional performance normally refers to performance parameters that are directly related to corresponding functions, e.g., lift coefficient. Complementary performance normally refers to products' service life, e.g., reliability. Typical objectives of DFP could be measurable capacity of a design including force, strength, stiffness, stress, aerodynamic properties, heat dissipation, and biomedical properties. For example, heterogeneous structure may result in better performance such as weight reduction, uniform stress distribution, and better cooling effects. However, in a traditional way, this kind of design concept is to be rejected because of manufacturability considerations. With the aid of AM, heterogeneous structures can be achieved in two levels. The first is the 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 (Watts and Hague 2006). The second is at meso or macro structure level. This type of heterogeneousness can be achieved by topology optimization or cellular structures.

2.2 AM-Related Design Method

Realizing the incompetence of conventional DTM in adopting the design freedom enabled by AM, many researchers have started to establish various design rules or guidelines to help successfully employ AM in building functional parts. Basically, these approaches can be divided into three categories: design guidelines, modified DTM, and design for additive manufacturing (DFAM).

2.2.1 Design Guidelines and Design Rules

In this category, the main goal is to establish a set of rules to guide design on the basis of full understanding of manufacturing constraints of various AM processes. Basically, this type of method could be regarded as the extension of DFM with a focus on AM. These rules are generally 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. There two main deficits of this kind of method: (1) with only one focus on manufacturability, it does not enhance performance improvement and (2) it requires designers to have much AM knowledge to interpret the rules.

As an example, the design guidelines for rapid manufacturing (RM) given by Becker et al. (Becker et al. 2005) are given as follows:

- 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 whether there are bionic examples to fit your tasks as these can give a hint towards better design solutions
- Feel free to use freeform designs; 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 it is no longer needed

Design guidelines focus on a more general discipline where designers are encouraged to make a better design by taking advantages of AM. 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 (Thomas 2010; Adam and Zimmer 2014; Popsecu 2007; Kruf et al. 2001; Kim and Oh 2008; Mahesh et al. 2004; Shellabear 1999). Research on design rules can be divided into two groups: experimental method, for example benchmark study, and systematic method. The former is represented by the research of Daniel (Thomas 2010). In his research, the geometric limitations of 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. A more effective way to verify design rules is to build a benchmark. In benchmark tests (Kim and Oh 2008; Mahesh et al. 2004; Shellabear 1999), 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 latter is represented by Adam and Zimmer (2014). 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 first defined as basic elements, element transitions, and aggregated structures. Then, after studying the attribute value, boundary conditions of these groups, design rules are obtained.

In addition, ASTM released general design guidelines (ASTM Standard 2012) for AM including design opportunities and limitations. Design opportunities cover layer by layer manner, possible sophisticated geometry, varied material or property, and design for functionality. Limitations of adopting AM as the fabrication method can be concluded as economical consideration, production volume, material choices, geometry discretization, building envelop, and post-processing. For the design aspect, geometry consideration, material property consideration, process consideration, product consideration, use consideration, sustainability consideration, communication consideration, and business consideration are all reported.

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 is only suitable for avoiding the restrictions of conventional design rather than providing how to take full advantage of AM-enabled design freedom. It is important to note that most of the design guidelines emphasize how to take advantage of AM capabilities, whereas the unprecedented limitations are rarely studied.

2.2.2 Modified DTM for AM

Adopting a precise and consistent design methodology to design a product is always suggested (Segonds 2011). Boyard et al. (2014) managed to put forward a modified DFMA methodology to improve the design process of AM related design. This design method consists of five steps: functional specifications, conceptual design, architectural design, detailed design, and implementation. It is characterized by the feature that DFA and DFM work in parallel simultaneously rather than sequentially. This feature is enabled by a modular and modifiable function graph in the conceptual design phase, where each function is represented by a sphere node and these nodes are linked by segments to indicate direct relationships 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 (Boothroyd et al. 2002). A function graph of sets was proposed to model a product and each set represents a part, different sets being connected by dotted lines (see Fig. 1). This kind of function graph allows users to recognize functions and functional relationships spatially. 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 whereas the relationship between A and B

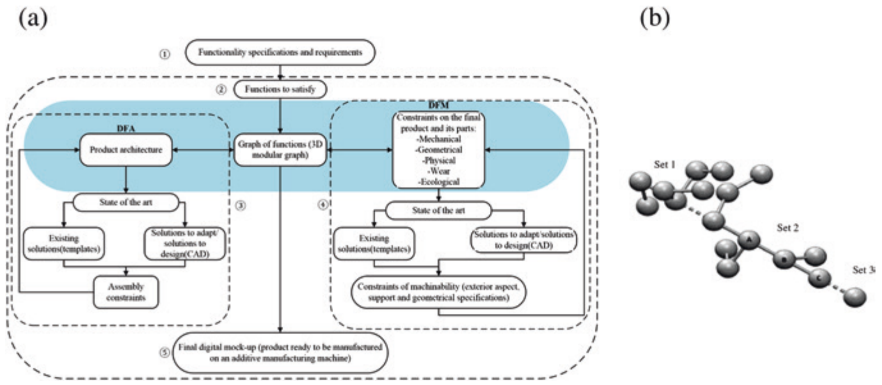


Fig. 1 Design methodology proposed by Boyard and Rivette (Boyard et al. 2014). **a** Modified DFMA method. **b** Function graph

is not defined. This proposed design methodology facilitates the idea of considering DFA and DFM simultaneously in AM design processes although it is not well developed for complete AM design innovation. For instance, it does not deal with a product incorporating inner relative movement and hierarchical complexity.

To develop a design methodology specially for AM, Rodrigue (2011) 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 products for preventing failure and to meet 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 examined to decide the structure and shape of the final product. This method concentrates more on design reliability whereas how to meet user requirements are not clearly discussed.

2.2.3 Design for Additive Manufacturing

Design for additive manufacturing (DFAM) could be regarded as the evolvement of design for rapid manufacturing (DFRM) in its early days. However, DFAM in this section is not referring to additive manufacturing as a manufacturing process. Instead, DFAM is focused on how to adopt the design freedom of AM fully to improve product performance. In other words, this section concentrates on design methods. These design methods for AM can be put into two groups. The first concerns AM-enabled structural optimization design methods, the second DFAM methodology.

Generally, structure optimization-related design methods are more specific with concrete objectives. AM-related structure design optimization methods can be classified by different objectives including stiffness, strength, compliance, and stress distribution in static structure design. In addition, structural optimization methods have spread to other disciplines such as dynamic (Evans et al. 2001; Ma et al. 2006), thermal (Zhou et al. 2004; Blouin et al. 2005; Rännar et al. 2007), and biomedical fields (Chen et al. 2011; Castilho et al. 2013; Faur et al. 2013). According to whether the optimization process considers manufacturing constraints, these optimization-related design methods can be grouped into two categories: unconstraint optimization and constraint optimization. In the early stages of design for AM, most researchers focus on the former to explore the potential of functionally optimal geometric design solutions. The means to realize optimal design could be a geometric way including parametric optimization, geometric optimization (shape, size, and topology), and cellular structures, or a material way, for example, functionally graded material. Taking topology optimization as an example, typical topology optimization methods include the ground structure method (Bendsøe et al. 1994; Dorn et al. 1964), homogenization method (Bendsøe and Kikuchi 1988), Solid Isotropic Material with Penalization (SIMP) method (Rozvany et al. 1992), level set method (Allaire et al. 2002; Wang et al. 2003), evolutionary method (Xie and Steven 1993; Young et al. 1999), and genetic method (Wang and Tai 2005; Chen et al. 2009). In contrast to topology optimization, cellular structures such as lattice can be optimized in terms of pattern (uniform or conformal), cell topology, strut thickness, material, orientation, lattice skins, and so forth. It is worth mentioning that it requires domain-specific knowledge to interpret some objectives to establish the relationship between design variables and objective functions for structural optimization problems. For example, to design a scaffold for tissue engineering, the desired structure is supposed to support the proliferation of cells. For constraint optimization method, manufacturability is greatly emphasized in the optimization process. A manufacturability check could be done simultaneously or iteratively with the help of design rules. Constraint optimization design method is becoming predominant in the industry when choosing AM as a new process. An overall DFAM computer aided system framework has been developed by Rosen (2007) consisting of part and specification modeling, process planning, and manufacturing simulation. In this design flow, the emphasis is placed on material and cellular structure modeling and optimization with respect to the manufacturing support module.

In contrast, DFAM design methodologies concentrate on how to design in a more general way without concrete objectives. They cover not only downstream design activities such as parametric optimization and DFM, but also certain upstream design activities such as functional design and part consolidation in the early design stage. Vayre et al. (2012, 2013) proposed a design method consisting of four steps: analyze the specifications, initial shape, parametric optimization, and validation of manufacturability. Manufacturing constraints are dedicated to laser-based or EBM-based AM processes including accessibility constraints, frequent acceleration and deceleration stages, heat dissipation, and inability to build closed hollow volume. This method indicates the need for functional design; however, the method is way too general so that how to generate initial shape and perform parametric optimization is not illustrated. Rosen (2007) and Tang et al. (2014) also indicate the need for satisfying the design specification and consider the extra step of how to conduct structural optimization to achieve multifunctional and multilevel design. In their design methods, multiple functions are explicitly referred to structural performance (i.e., stiffness or stress distribution) and conjugate heat transfer or vibration absorption, and multilevel design is strictly limited to cellular structures. These methods share a common deficit that manufacturability is not considered and the initial design space is given. To incorporate the capability of AM in realizing part consolidation, Yang et al. (2015) proposed a new part consolidation method to integrate function integration with structural optimization to achieve a better performance and lower part count with respect to manufacturing constraints, assembly requirements, and modularization requirements. One of the main contributions is that it proposes a feasible way to deal with assembly design in the context of AM, which is one of the main deficits of most current designs for AM research because assembly is not considered.

Design is always creative work, especially the early design stage. Although how to optimize structure and achieve function integration is becoming known, producing certain creative shapes or structures could be exhausting without a good knowledge of AM. To ease the difficulty of coming up with innovative shapes, a feature-based design approach was proposed by Bin Maidn (2011). These design features serve as an inspiration for designers in the conceptual design stage. However, several issues remain unsolved including the AM feasibility validation approach adopted in the system and how to do morphing on the basis of given examples.

In conclusion, the most promising changes brought by AM are the freedom to achieve complex geometric shape, material distribution, material composition, and function integration. When these changes come to the design process, they can be realized by structural optimization and function integration. However, both structural optimization and function integration happen in the downstream design flow. The need to explore the early design stage becomes urgent. The following issues are meant to be solved in the near future (Fig. 2):

1. Almost all the optimization design methods start with existing design which may jeopardize the potential of finding optimal design solutions because the original design is originally compromised.
2. The potential of AM in realizing function integration is seldom developed and most of the existing design are case-study-based. There is no theoretical framework to support function integration.
3. Although AM may help eliminate the need for assembly for some components, the constraints of any remaining assembly needs to set a new challenge for designing AM.

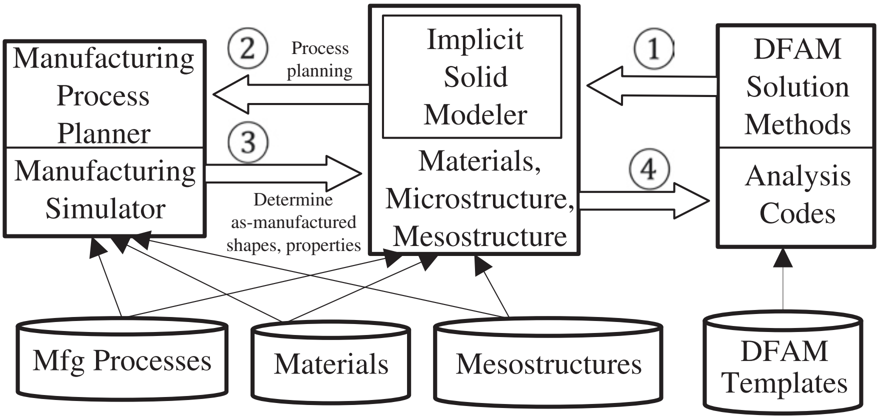


Fig. 2 DFMA system and overall methods (Rosen 2007). Adapted with permission

2.3 *On-Going AM-Related Design Research on Sustainability*

Additive manufacturing draws more and more attention for its great potential for sustainability because it has much improved materials efficiency, no-tooling manufacturing fashion, reduced life cycle impacts, and greater engineering functionality compared to subtractive manufacturing processes. As indicated by some researchers, 80 % of the environmental damage of a product is established after 20 % of the design activity is complete (Otto and Wood 1998). Therefore, identifying environmental impact factors in the early product development stage is critical.

AM-related design research on sustainability could be grouped into two categories on the basis of whether it is compared to conventional manufacturing processes. The first category is focused on the assumption that AM benefits the environment through a lightweight structure, less material consumption, and less energy loss. Huang et al. (2015) systematically estimated net changes in life cycle primary energy and greenhouse gas (GHG) emission for the adoption of metallic lightweight aircraft components fabricated by AM processes by the year 2050 to shed light on environmental impacts. In their study, it is indicated that cumulative energy savings could at most reach 1.2–2.8 billion GJ and GHG could have a reduction as high as 92.1–215.0 million metric tons. Some researchers (Mognol et al. 2006; Kellens et al. 2010; Baumers et al. 2011) also conducted similar quantitative studies on AM processes where only in-process energy consumptions are measured. Some researchers (Telenko and Conner Seepersad 2012) also include the energy consumption of raw material.

The second category concentrates on studying the difference between conventional manufacturing processes and AM in terms of detailed factors including material consumption, energy cost, hazardous material, and recyclability. Kreiger and

Pearce (2013) carried out experiments and LCA in terms of in-process energy consumption with case studies of blocks, spout and juicer being used to compare to injection molding. Wilson et al. (2014) also carried out experiments and LCA with respect to remanufacturing of a turbine blade with LENS to compare energy consumption compared to two arc welding processes (GTAW, PTA) and casting a new blade. Faludi et al. (2015) comprehensively compared the impact on environment in terms of AM and milling with respect to major ecological impact including energy use, waste, toxins, etc. as well as environment impact such as climate change, toxicity, and land use. According to their analysis, the assumption of AM eliminating waste is not necessarily true.

In conclusion, most researchers are at the early stage of exploring the potential opportunities and impact of AM on environment either by quantifying the effect of manufacturing process or life cycle analysis. However, how to improve LCA scores of products fabricated by AM in product development process is seldom studied. This study is therefore filling the spot of developing a design framework to secure product functionality with sustainability as a priority.

3 Sustainable Design Methodology for AM

From the brief review of AM-enabled design methods in the previous section, it is manifested that most existing design methods for AM are aiming at the improvement of products' functional performance. As to the sustainability of products fabricated by AM processes, most researchers are focusing on evaluating and minimizing the environmental impact of AM processes. However, it should be noted that those AM-enabled design methods may also play an important role for the sustainable product, because decisions made at the initial product design phase may also determine the environmental and economic impacts of future decisions (Harper and Thurston 2008). Thus, to reduce the product's environmental impact, it is necessary to link those AM-enabled design methods with the environmental impact evaluation model of AM processes. To achieve this goal, a general design methodology is proposed and described in this section. This general design methodology mainly focuses on the reduction of the environmental impact of the product's manufacturing process by taking advantage of AM technologies. It assumes the product's environmental impacts during other major life cycle stages are unchanged. This assumption is supported by a given design requirement which includes the restriction of the product's size, weight, or other parameters which may increase the product's environmental impact during other life cycle stages. In the following, the overall framework of the proposed methodology is first presented. Then four major design stages of this overall design framework are discussed, respectively, in each section.

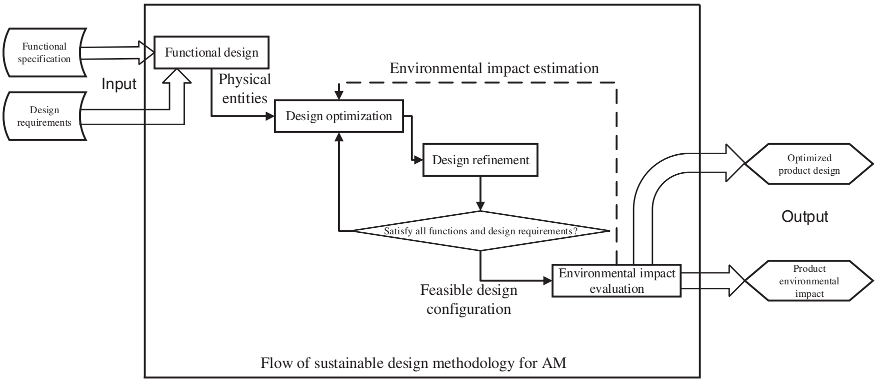


Fig. 3 General framework of sustainable design methodology for AM

3.1 General Design Flow

The general workflow of the proposed design methodology is shown in Fig. 3. The inputs of this design methodology are the product's functional specification and related requirements. In a functional specification, all major functions of a designed product should be declared, whereas in design requirements, the product's non-functional design constraints such as price, size, and weight are described.

The outputs of this proposed design method are an optimized design and its environmental impact. Generally, the whole design workflow can be divided into four stages—functional design, design optimization, design refinement, and environmental impact evaluation. In the functional design stage, physical entities are determined based on the product's functional specification. In the second stage, those AM-enabled design optimization methods can be used to minimize the product environmental impact. In this design stage, the feedback of environmental impact estimation needs to be considered. This feedback is characterized by the relationship between those design parameters of a product and its environmental impact. The product's environmental impact is considered to be one of the major design objectives during this design stage. After the design optimization stage, an initial feasible design solution can be generated. This initial design solution needs to be refined based on the manufacturability of the selected AM process, and the assembling ability of designed products also needs to be evaluated and considered. Some assembly features can be added. At the end of the design refinement stage, designers should check whether the refined design can satisfy all functions and design requirements from the input. If not, it should go back to the design optimization stage to modify the design parameters. Otherwise, it can go to the environmental impact evaluation stage where an environmental impact evaluation model can be applied to calculate the environmental impact of product's manufacturing process.

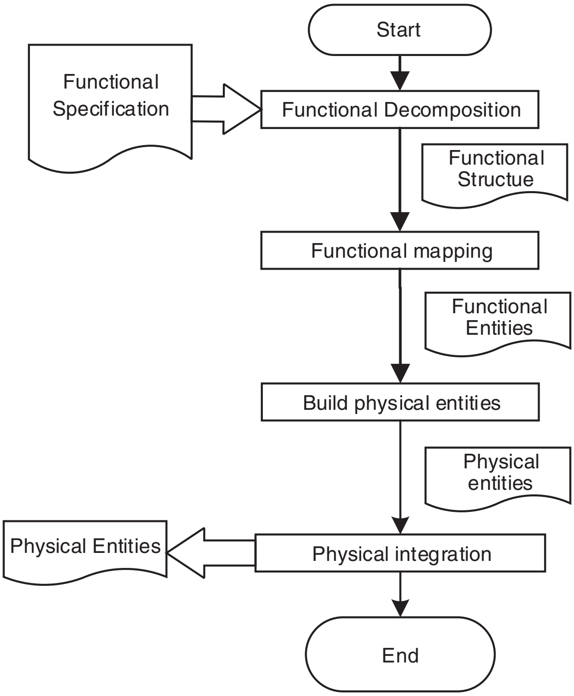


Fig. 4 Design flow of functional design stages

3.2 *Functional Design*

The general design steps of the functional design stage are shown in Fig. 4. The major input of this design stage is a functional specification. A functional specification usually defines the overall functions of a product and some requested input and output properties. It usually does not define the internal working process of a product. Generally, designers can summarize the interaction between designed products and its external agent, e.g., users, material, and energy, based on the input functional specification. A generic black box model can be used to represent the input functional specification which is shown in Fig. 5.

For those products that only play a single or several basic functions, it is not difficult to find directly their corresponding physical features to fulfill their functional requirements. However, if designers cannot find directly feasible physical features to meet directly the overall functions of a product, a functional decomposition process is needed. In this chapter, functional decomposition refers to a process which resolves the overall functions of a designed product into a set of

Fig. 5 Generic black box model for product functional specification

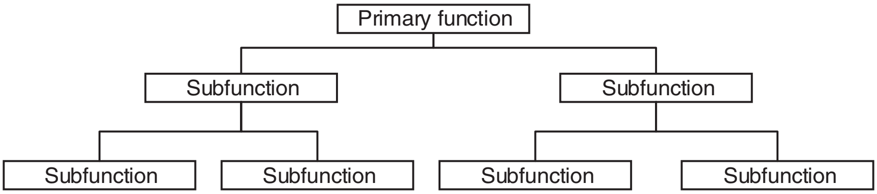


Fig. 6 Generic format of functional tree

interlinked subfunctions in such a way that the original functions can be fulfilled by implementing all subfunctions. These subfunctions and their interlinked relationship are defined as a functional structure which is the output of a functional decomposition process.

An elementary approach for functional decomposition is to decompose hierarchically the input functions of a designed product into a tree structure, usually known as a functional tree (shown in Fig. 6). The functional tree is easy and fast to build. However, it only contains hierarchical relationships between subfunctions, and fails to describe the interaction between different functions. To describe the interaction between different subfunctions and their relations to the overall functions of a product, a black box functional model (shown in Fig. 7) can be used in the functional structure.

In this functional structure, a basic function is described with a simple black box whose input and output are clearly defined, as shown in Fig. 7a. Different basic functions are interlinked according to the energy, material, and information flow. The generic format of this type of functional structure is shown in Fig. 7b. Compared to the functional tree, the functional structure based on a black box model contains more information and also needs more time to construct. This type of functional structure can be an efficient tool for designing a product with complex functional interaction. Generally, according to the functional complexity of a designed product, designers can select an appropriate functional structure. For the detailed steps of constructing different types of functional structure, the reader can refer to (Otto and Wood 2001).

After functional decomposition, a functional structure can be obtained. A functional mapping is needed to map the obtained functional structure into physical features and its relations. At the current stage, the referred physical feature is not assigned with detailed geometry and material information. It is an abstract entity only with the information of its physical behavior which can be used to implement its corresponding function. Thus, these entities obtained from functional mapping are called functional entities. These functional entities are usually searched based on designers' experience or knowledge in the current design step. However, because AM-enabled design features have not been widely used, designers usually lack awareness of these features. This can be a barrier to taking those AM-enabled features to reduce environmental impact. To overcome this barrier, an

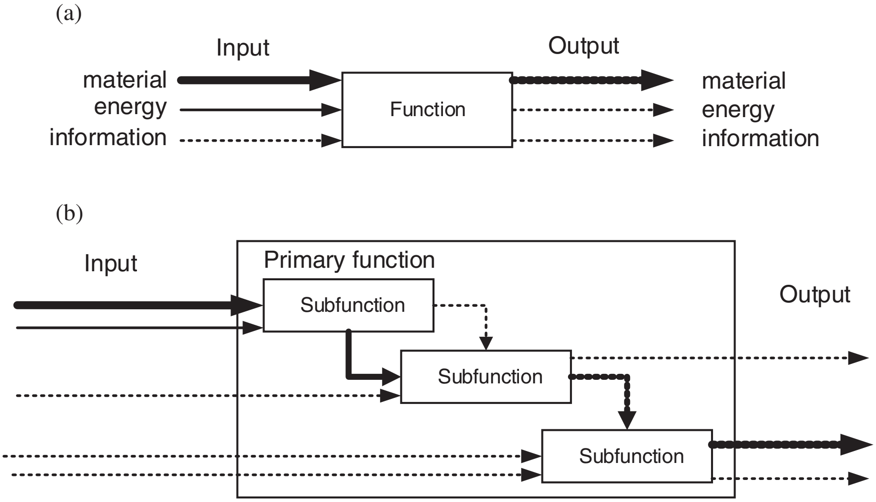


Fig. 7 Generic format of functional structure based on a *black box*. **a** *Black box* of basic function. **b** Generic format of functional structure

AM-enabled design feature database or knowledge base is needed. For example, an AM-enabled feature database has been built by Maidin et al. (2012) to inspire designers.

It should also be noted that the relationships between basic functions in a functional structure and their corresponding functional entities are not always in one to one correspondence. Indeed, one basic function can always find one corresponding functional entity. However, one functional entity is not necessary to serve only one basic function. In some cases, a functional entity can serve several basic functions simultaneously. The process of mapping several basic functions into one functional entity is known as functional integration. An engine of a car is an example of functional integration. In the functional design of a car, an engine can be regarded as a functional entity. It serves two different functions. First, it can transfer the fuel energy into kinetic energy. Second, it also generates heat for the heating system. Thus, it can also play a role as a heater. Obviously, functional integration can reduce the number of functional entities needed, which may lead to the reduction of the overall parts' count. However, it may also cause some issues. One of the most serious issues that functional integration may bring is the functional coupling. These basic functions are coupled when they are all served by the same functional entity. The design parameters of this functional entity may affect the function performance for different function simultaneously. Thus, difficulties may arise in the following design steps in deciding the detailed design parameters of this functional entity. Thus, functional integration is not suggested by some existing design methodologies, such as axiomatic design theory (Suh 1998).

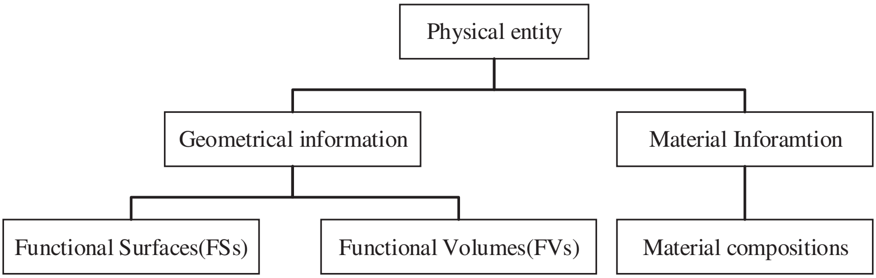
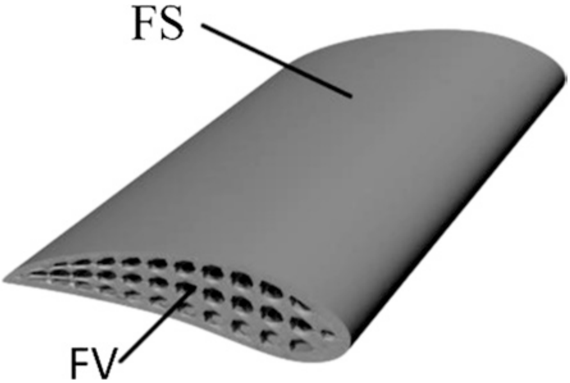


Fig. 8 Graphic view of data structure for physical entity

Fig. 9 FS and FV of airfoil



The next step of functional design is to construct concrete entities to realize the physical behavior described by obtained functional entities. This concrete entity should contain two types of information, geometrical information and material information. In this chapter, a concrete entity built in the current step is referred to as a physical entity. The graphic view of a physical entity's data structure is shown in Fig. 8. To represent the geometrical information of a physical entity, concepts of Functional Surfaces (FSs) and Functional Volumes (FVs) are used. In this chapter, an FV is defined as a geometrical volume of functional entity, whereas an FS is a key surface of a functional entity for its physical behavior. For example, Fig. 9 shows the physical entity of an airfoil. The outer surface of this airfoil is the key surface which plays an air dynamic role. The whole structure of this airfoil is the FV. In this FV, a lattice structure is used to reduce its weight.

In the current design stage, because of the incomplete information grasped by designers, it is impossible to make a final decision on the exact shape of FSs and FVs. Thus, the defined FSs and FVs at the current stage are changeable and deformable surfaces or volumes. A parametric modeling method can be used to describe those deformable surfaces or volumes. In this chapter, a parameter vector θ is used to control the shape of FSs or FVs. The set of all allowable value for the parameter is denoted $\Theta \subseteq \mathcal{R}^k$ where k is the dimension of a parameter vector.

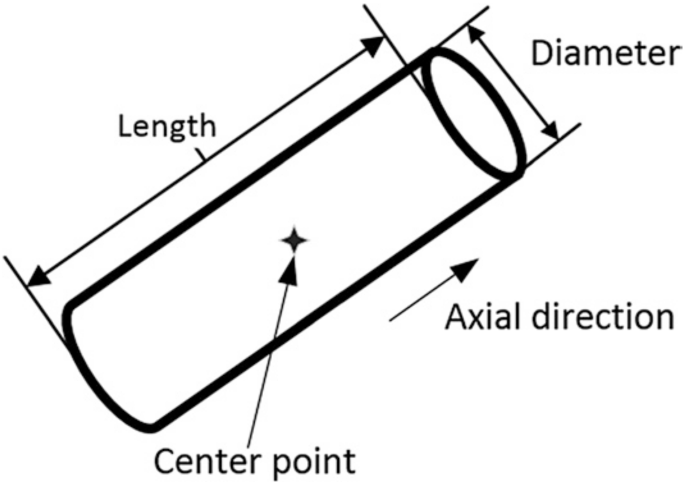


Fig. 10 FV in cylindrical shape

This dimension is also known as Design Degrees of Freedom (DDoF). For different types of geometry element, there are different parametric modeling methods. Most existing CAD software provides the capability to describe a simple geometrical element with several independent parameters. For example, four independent parameters can be used to describe an FV of a cylinder bar. They are a center point, axial direction, diameter, and length, which are shown in Fig. 10. To realize its corresponding functional requirements, some parameters of FSs and FVs need to be fixed. For instance, if the FV shown in Fig. 10 is designed to fit a hole with a certain diameter and axial direction, both diameter and axial direction of this FV should be fixed with given values. Thus, the DDoF of this FV is two.

Because of the constraints of traditional manufacturing, designers at the current stage traditionally tend to assume FVs and FSs in a simple geometry with the small number of DDoF. These assumptions can greatly reduce the complexity in following design processes. Moreover, the product can be generated with regular geometry, which is easy manufacturing. However, whether these FSs and FVs are optimized with respect to functional performance or environmental impact is hard to decide. For example, Fig. 11 shows a design case of a physical entity with one FV and two FSs to sustain a normal pressure P on surface C with fixed end at surface A. To realize this physical behavior, most experienced designers may select the "I" shape beam as an FV for this physical entity to sustain the bending moment. However, the result of topology optimization shows the irregular truss-like shape structure may achieve the same stiffness with less material than the regular "I" shape. Thus, to take advantage of design freedom provided by AM technologies, the parametric modeling methods, which can deal with complex geometrical shapes, are needed to describe the FSs and FVs of physical entities which are to be fabricated by AM processes. For example, a complex FS

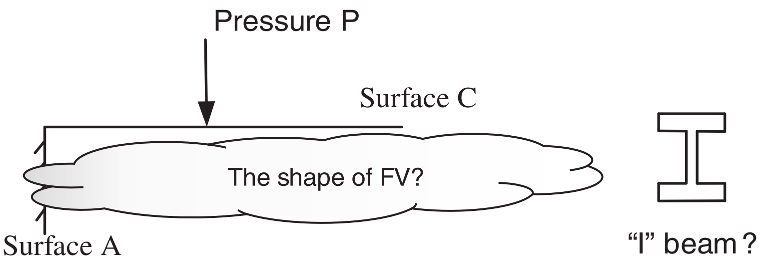


Fig. 11 Simple FV versus complex Fv

can be represented by a NURBS (Non-Uniform Rational B-Splines) surface. The positions of control points can be regarded as parameters to describe this FS. As to FV, a voxel-based geometrical modeling method can be used to describe the complex geometry of FV. The scalar value at each voxel point is the parameter to control the shape of FV. If this value is larger than zero, this voxel point is considered in the FV, or else this voxel point is out of FV. Indeed, using an FS or FV with more DDoFs may increase the complexity in the following design process. However, those AM-enabled design methods discussed in Sect. 2 are able to deal with a large number of DDoFs to generate an optimized result with respect to both functional performance and environmental impact.

Besides geometrical shape, an appropriate material is also needed to be decided for each physical entity at the current step. The classical material selection method based on a material chart (Ashby and Cebon 1993) can be used here to help designers select the material which can achieve the required physical phenomenon with the minimum environmental impact.

At the end of the functional design stage, to reduce further the product's part counts, some physical entities can be merged into one physical entity. This process is known as physical integration. Based on the general capability of AM processes, some simple rules for physical integration are provided in this chapter. The two physical entities satisfying all these rules can be considered as candidates for physical integration.

Rule 1: There is no relative movement between two physical entities.

Rule 2: Material of two physical entities is compatible with respect to a certain manufacturing process.

It should be noted that the two rules mentioned above are only necessary conditions that integrated physical entities should have. More detailed manufacturing and assembly information is also needed for designers to make the final decision. For those integrated entities, the FSs which play roles as connection surfaces between them can be removed, and the connected FVs can be merged together. One example of physical integration is a four-sided grater which is shown in Fig. 12. To design this product, each side of grater itself is originally the physical entity which is used to grate the vegetable into different shapes. In this step, designers can combine these four independent physical entities into one part. It is clear that their

Fig. 12 Four-sided grater

original FSs for grating are still kept and independent. However, the overall part count has been decreased. As with the functional integration process mentioned during the second step of the current design stage, the physical integration process can also reduce the overall part count of a designed product. However, the functional entities and their related FSs and FVs still remain independently inside the integrated physical entity. Thus, functions implemented by this physical entity are still decoupled. The physical entities built at the end of the functional design stage are regarded as the input in the following multiscale design optimization stage.

3.3 Design Optimization

In the second stage, a design optimization process can be applied to the physical entities obtained to minimize product environmental impact while improving its functional performance. The design parameters of FSs and FVs are regarded as the design variables of this optimization process. Moreover, the pre-feedback of the environmental impact model is considered with those multiscale AM-enabled design optimization methods described in Sect. 2. Its general work flow is shown in Fig. 13.

This workflow can be divided into four steps. At the beginning, the objective of the optimization process is determined based on the pre-feedback from the environmental impact model. Then functional requirements and manufacturing constraints are converted to the constraints on the design parameters. After that, according to the major function played by a designed physical entity, an

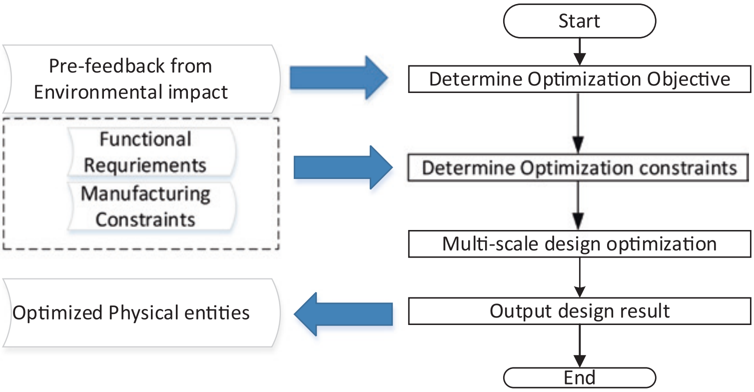


Fig. 13 General work flow of optimization process

AM-enabled design optimization method can be select to optimize this physical entity on different design scales. At the end, the design result is output to the next design stage for design refinement. In the following paragraphs, the detailed design steps of this design stage are discussed in detail.

First of all, to determine the objective of the following optimization process, the pre-feedback of the environmental impact model on the selected AM manufacturing process needs to be considered. The detailed discussion on the environmental impact model of the AM manufacturing process is given in Sect. 3.5. In the optimization process discussed in this section, the environmental impact evaluation model is considered as a function which can expressed as

$$I_e = f\left(p_{\text{design}}, p_{\text{machine}}, p_{\text{material}}, p_{\text{operation}}\right) \tag{1}$$

where I_e is a vector of environmental impact indexes such as midpoint indicators of ReCiPe, $p_{\text{design}}, p_{\text{machine}}, p_{\text{material}}, p_{\text{operation}}$ are the vectors of design-dependent, machine-dependent, material-dependent, and operation-dependent parameters for the environmental impact evaluation model, respectively. The function shown in (1) only depends on the type of AM process selected. For different types of AM processes, the form of function might be different.

During the optimization of each physical entity, the type of manufacturing process needs to be predetermined based on the selected materials and the shape of FSs and FVs. Once the type of AM process is determined, the form of function f shown in (1) can be obtained. Based on this function, the first round of the minimization process can be used to find the design-dependent parameters $p_{\text{design}}{}^*$, which can achieve the minimum environmental impact. During the optimization process, other independent variables in function f are unchanged. It should be noted that some elements in the vector in the $p_{\text{design}}{}^*$ might equal zero or infinity. This value is regarded as the pre-feedback of the environmental impact model on the design process. This pre-feedback can be set as the design objective during the following optimization process.

The second step is to build the constraints for the optimization process. At the current stage, design constraints are from two main streams. The first stream is the functional requirements. To fulfill the described functions for each physical entity, the design variables of FSs and FVs for each physical entity should satisfy certain conditions. These conditions can usually be described by the governing equations of the physical entity's corresponding physical behavior. The general form of this type of conditions can be expressed as

$$g(x, y) = 0, c(y) > 0 \tag{2}$$

where g represents the governing equations of the physical entity's behavior, x is the vector of design variable for the given physical entity, y is a vector of the state variables to describe the physical behavior of entities, and c represents the conditions of the state variables.

Besides those functional related constraints, the capability of the selected AM process is another main stream for design constraints. Although the AM process can fabricate a part with an extremely complex shape, it still has certain limitations. For example, support structures are needed for certain types of AM processes and some of these support structures are difficult to remove because of inaccessibility. Thus, during the optimization process of physical entities, the manufacturing constraints also need to be considered.

Based on the obtained design objective and constraints, the design can be described so as to find design variables for physical entities which can achieve the optimized design-dependent parameters $p_{\text{design}}{}^*$ while satisfying all the functional requirements. Thus the optimization problem can be expressed as

$$\begin{aligned}
&\text{Min. } |p_{\text{design}}(x) - p_{\text{design}}{}^* \\
&\text{S.T. } g_i(x, y) = 0,\ c_i(y) > 0,\ i = 1, 2, 3 \ldots l \\
&m_i(x) > 0,\ j = 1, 2, 3, \cdots k
\end{aligned} \tag{3}$$

where $|n|$ denotes a norm of vector n, x represents a vector of design variable for physical entity, $p_{\text{design}}(x)$ is a function which can map design variables of physical entities into the design-dependent parameters for environmental impact model, $g_i(x, y) = 0$, $c_i(y) > 0$ is the constraint from the ith function of the physical entity, and $m_i(x) > 0$ is the constraint from manufacturability of a selected AM process.

To solve the optimization problem stated in (3), various AM-enabled design optimization methods described in Sect. 2 can be used. However, most existing design optimization methods focus on improving the functional performance of the designed physical entity. Thus, sometimes it is difficult to apply directly those optimizations to solve the optimization problem defined in Eq. 3. To deal with this problem, designers can convert the objective function in (3) into the constraints of structural optimization problems. Consider a sequence of design-dependent parameters p_{design} which can be denoted as $L = (p_1, p_2, \ldots p_n, \ldots, p_m, \ldots)$. This sequence of design-dependent parameters satisfies the following condition: for any n, m, if $n < m$, then $\left|p_n - p_{\text{design}}{}^*\right| > \left|p_m - p_{\text{design}}{}^*\right|$. Based on this sequence of design-dependent parameters, the optimal p_{design} can be searched by the algorithm presented in Fig. 14.

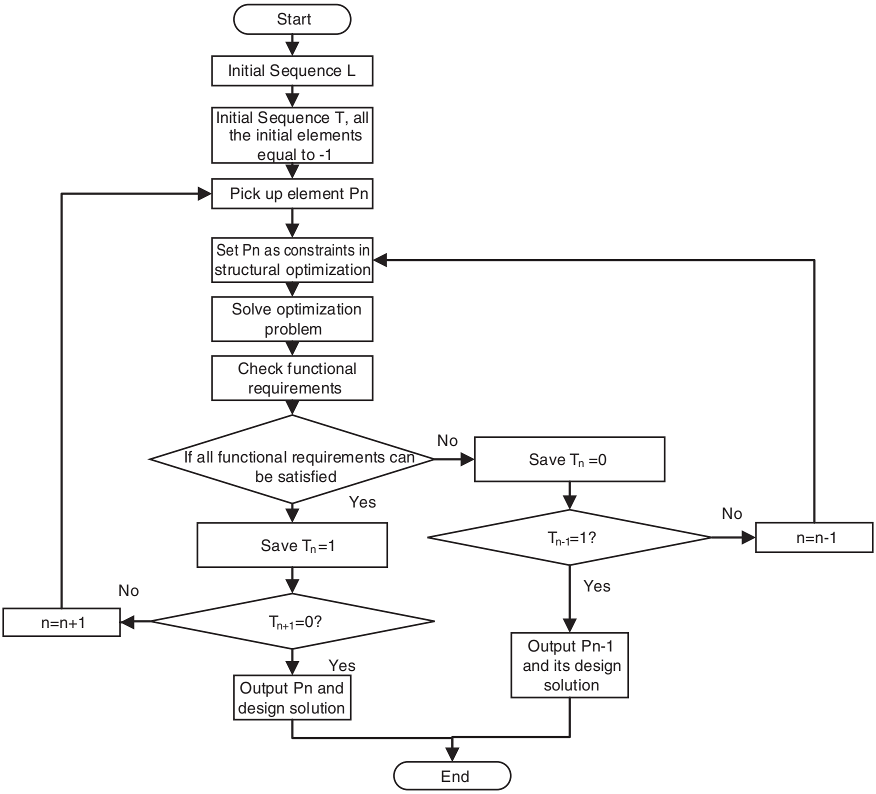


Fig. 14 Algorithm to find the optimized design solution for minimum environmental impact based on existing structural optimization methods

3.4 Design Refinement

After the design optimization stage, a design refining process is needed to modify further some detail features of optimized product design because of the coarse boundary or irregular boundary obtained from the second design stage. Especially for those physical entities designed with the relative density based topology optimization method, the result of the optimization process is a relative density distribution in the FVs. Thus, at the design refinement stage, designers need to choose a method to deal with gray regions where the relative density is between 0 and 1. The simplest way is to set a threshold of relative density. In the region where the relative density is lower than this threshold, the material is removed. This method is simple but may cause some unforeseen problems. For example, if the threshold is too small, the optimized FV of physical entity might be divided into several separated portions. Otherwise, the big threshold leads to too much material left at the end, which cannot achieve the optimized design. Thus, designers should be careful to check the threshold at the design refinement stage.

Besides smoothing the boundary shape of physical entities, another important factor that needs to be considered at the design refinement stage is the assembling ability of a designed product. At the current stage, because the geometrical shapes of most physical entities are already determined, designers can use existing rules or design guidelines to assess the assembling ability of a designed product. To improve the product's assembling ability, some physical entities may need to be divided into several different parts and assembled together. Even though, the separation of a physical entity may increase the overall part counts, it may reduce the difficulty of the product assembly process. At the end of the design refinement stage, the assembly features can be added to the obtained physical entities based on their assembly relationships.

3.5 Environmental Impact Evaluation

In this section, the environmental impact evaluation method for AM processes is discussed. General analysis flow of the product's environmental impact evaluation model for AM processes is shown in Fig. 15. This general flow can be divided into three main steps: energy and material consumption analysis, Life Cycle Inventory (LCI), and Life Cycle Impact Analysis (LCIA) compilation. In the following paragraphs, the binder jetting process, one of the major AM processes, is used as an example to illustrate the detailed steps of environmental impact evaluation for a given AM process.

According to the general flow shown in Fig. 15, the first step is to calculate the energy and material consumption of a designed product via a given AM process. To achieve this purpose, the manufacturing process of the selected AM technique is first analyzed. Generally, the whole manufacturing process of a binder jetting technique can be divided into four steps: printing, curing, depowdering, and sintering. The core step of the binder jetting process which differentiates it from other AM technologies is the printing process. It is difficult to evaluate directly energy and material consumption of the printing process, because this process consists

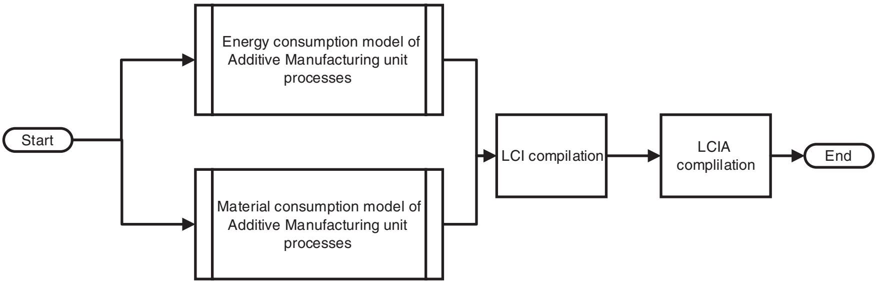


Fig. 15 Workflow of environmental impact evaluation

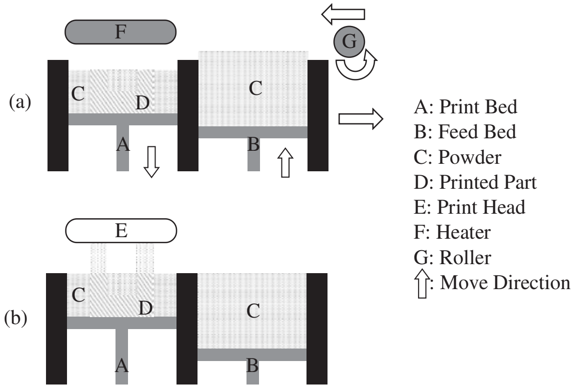


Fig. 16 Working principle of printing process for the binder jetting technique

of three subprocesses: spreading, printing, and heating. As showed in Fig. 16a, a printing process starts by lowering the print bed by one layer thickness and lifting the feed bed by one layer thickness. Then the roller spreads one layer of powder materials from the feed bed to the print bed. This process is known as spreading. Then the print head E deposits a pattern onto the powder with binder material, thus forming a printed layer. This subprocess is known as printing a binder. After one layer is finished, the step motor system moves the print bed under an electrical infrared heater to dry the binder. This subprocess is known as heating. After one layer of printing, the machine automatically repeats this process until the part is completed.

Besides these subprocesses, the printing preparation process also needs to be considered in the binder jetting process. To summarize the manufacturing processes mentioned above, the IDEF0 model of the binder jetting process is established and shown in Fig. 17. Based on the IDEF0 model of the binder jetting process, an LCA process model is built on UMBERTO NXT LCA software which is shown in Fig. 18. The parameters related to subprocesses of LCA process model shown in Fig. 18 are predefined. These parameters can be divided into four types: machine-dependent parameters, operator-dependent parameters, material-dependent parameters, and design-dependent parameters. These four types of parameters are summarized in Tables 1, 2, 3, and 4 respectively.

For each of the entities modeled in UMBERTO NXT LCA software, a mathematical expression for each activity is first developed. The detailed discussion of this mathematical modeling can be found in (Meteyer et al. 2014). Here, only a summary of those mathematical models is listed.

Energy consumption models:

Infra-red heater

The infra-red heater power is set as a percentage of its maximum power by the operator on the machine and is running during the entire process. The heating

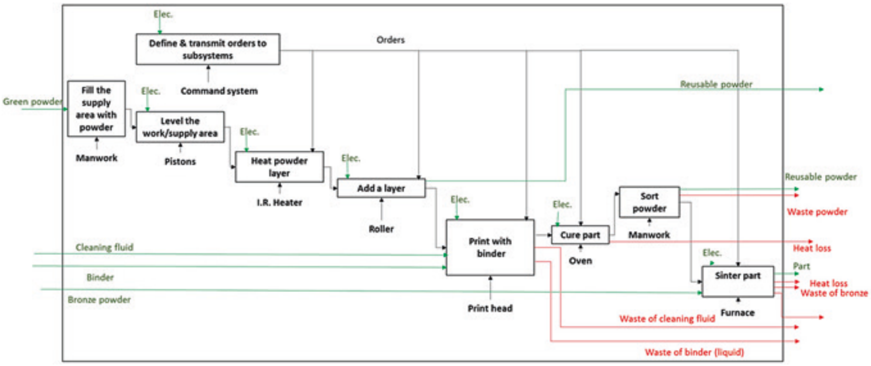


Fig. 17 IDEF0 model of a binder jetting process

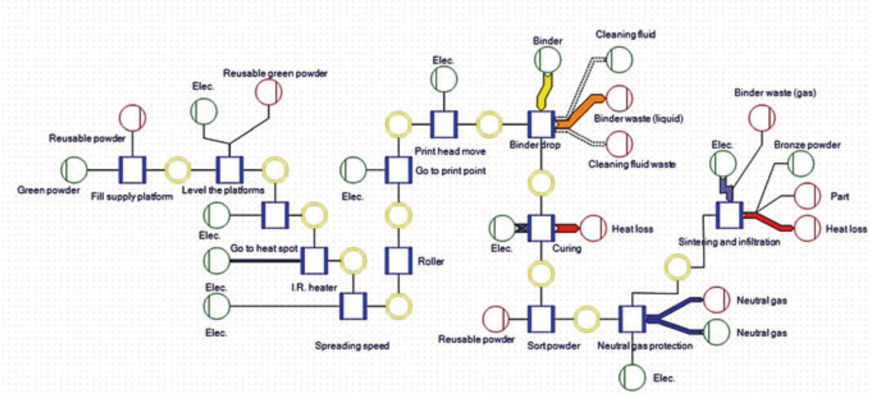


Fig. 18 The LCA unit process model of binder jetting unit process

time of the powder is defined by the time the platform stays under the heater. The energy used by the heater is defined by

$$E_{\text{heater}} = \frac{\left(\mathrm{P}_{\max} \times \%\text{heater} \times t_{\text{process}}\right)}{\text{Eff}_{\text{heater}}} \tag{4}$$

with

$$t_{\text{printing}} = \frac{H_{\text{part}} \times t_{\text{layer}}}{H_{\text{layer}}} \tag{5}$$

The maximum electrical power used by the heater is measured and the maximum power of the heater is found in the machine documentation.

Table 1 Machine-dependent parameters

Machine-dependent parameters		
Parameter	Symbol	Unit
Volume of supply platform	V_{supply}	mm^3
Screw diameter	D_{Screw}	mm
Mass of platforms	M_{platform}	kg
Platforms' section	S_{platform}	mm^2
Screw's pitch	p	mm
Efficiency of transmission for supply and part build platforms	$\eta_{\text{transmsupply/partbuild}}$	%
Efficiency of motors for supply and part build platforms	$\eta_{\text{motsupply/partbuild}}$	%
Friction coefficient in screw-nut systems	$f_{\text{screw - nut}}$	Unit
Mass of chariot	M_{chariot}	kg
Friction coefficient in chariot's guiding	$\mu_{\text{slideways}}$	Unit
Distance print spot-heat spot	$L_{\text{print}-\text{heat}}$	mm
Efficiency of pulley-belt for roller	$\eta_{\text{pulley - belt}}$	%
Efficiency of motor for chariot	$\eta_{\text{motroller}}$	%
Maximum power of infrared heater	$P_{\text{heatermax}}$	W
Furnace volume	V_{furnace}	mm^3
External pressure	p_{ext}	Pa
Pump's mechanical efficiency	η_{pump}	%
Distance spreading	L_{spread}	mm
Distance end of spread spot-print spot	$L_{\text{spread - print}}$	mm
Print-head stroke	L_{phstroke}	mm
Mass of print head	$M_{\text{print - head}}$	kg
Friction coefficient in print-head guiding	$\mu_{\text{print - head}}$	Unit
Efficiency of rack and pinion for print-head	$\eta_{\text{r\& p}}$	%
Power of uncapping	P_{uncap}	W
Specific heat capacity of the apparatus for curing	$Cp_{\text{apparatus}}$	J/kg/K
Specific heat capacity of the recipient for sintering	$Cp_{\text{recipient}}$	J/kg/K
Specific heat capacity of the support powder	$Cp_{\text{supportpowder}}$	J/kg/K
Specific heat capacity of the infiltrant	$Cp_{\text{infiltrant}}$	J/kg/K
Surface of oven	S_{oven}	mm^2
Convection coefficient inside the oven	h_{intoven}	W/m2/K
Convection coefficient outside the oven	h_{extoven}	W/m2/K
Convection coefficient inside the furnace	$h_{\text{intfurnace}}$	W/m2/K
Convection coefficient outside the furnace	$h_{\text{extfurnace}}$	W/m^2/K
Thermal resistance of oven wall	R_{oven}	m^2 K/W
Thermal resistance of furnace wall	R_{furnace}	m^2 K/W
External temperature	T_{ext}	K
Mass of recipient for sintering	$M_{\text{recipient}}$	Kg

Table 2 Operator-dependent parameters

Operator-dependent parameters		
Parameter	Symbol	Unit
Percentage of filling supply platform	$\%_{\text{filling}}$	%
Mass of reused powder	M_{reused}	kg
Layer thickness	δ	mm
Feed ratio	R_{feed}	Unit
Percentage of heater's maximum power	$\%_{\text{heater}}$	%
Vacuum pressure desired	p_{fin}	Pa
Argon flow-rate	D_{vAr}	mm^3/s
Mean time between two consecutive layers	t_{layer}	s
Number of overlaps	N_{overlaps}	Unit
Saturation ratio	R_{sat}	
Mass of binder waste per layer	$M_{\text{binder/layer}}$	kg
Mass of cleaning fluid waste per layer	$M_{\text{clean/layer}}$	kg
Mean time to print a layer	$t_{\text{printlayer}}$	s
Mean temperature during curing	$T_{\text{meancuring}}$	K
Total duration for curing	$t_{\text{totalcuring}}$	s
Duration of maintain phase for curing	$t_{\text{maintaincuring}}$	s
Mean temperature during sintering	$T_{\text{meansintering}}$	K
Total duration for sintering	$t_{\text{totalsintering}}$	s
Duration of maintain phase for sintering	$t_{\text{maintainsintering}}$	s
Infiltrant ratio	$R_{\text{infiltrant}}$	Unit

Table 3 Material-dependent parameters

Material-dependent parameters		
Parameter	Symbol	Unit
Density of powder	ρ_{powder}	g/mm^3
Packing ratio	$\%_{\text{pack}}$	%
Proportion of reusable powder	$\%_{\text{reusable}}$	%
Density of binder	ρ_{binder}	g/mm^3
Specific heat capacity of the powder	Cp_{powder}	J/kg/K

Table 4 Design-dependent parameters

Design-dependent parameters		
Parameter	Symbol	Unit
Height of part	h_{part}	mm
Volume of part	V_{part}	mm^3

Curing

The curing oven is modeled as a hermetically closed oven the walls of which are made of one material of surface thermal resistance R. Estimation of this resistance is discussed later. The curing profile consists of a linear increasing of the temperature and a maintained period for the final temperature. The energy needed is split into the energy for heating the powder and the apparatus and the energy needed to maintain the temperature in the oven.

$$E_{\text{heating}} = \left(M_{\text{powder}} \times Cp_{\text{powder}} + M_{\text{support}} \times Cp_{\text{support}}\right) \times \Delta T \tag{6}$$

$$E_{\text{maintain}} = \int_0^{t_{\text{fin}}} \frac{S_{\text{oven}} \times (T(t) - T_{\text{ext}})}{R + \frac{1}{h_{\text{int}}} + \frac{1}{h_{\text{ext}}}} \times \text{d}t \tag{7}$$

$$E_{\text{maintain}} = \frac{S_{\text{oven}} \times (T_{\text{mean}} \times t_{\text{increase}} - T_{\text{maintain}} \times t_{\text{maintain}})}{R_{\text{oven}} + \frac{1}{h_{\text{int}}} + \frac{1}{h_{\text{ext}}}} \tag{8}$$

Sintering

The sintering profile consists of several linear temperature increases followed by a maintained temperature. By analogy, the sintering energy is defined as

$$\begin{aligned} E_{\text{heating}} = (M_{\text{powder}} \times Cp_{\text{powder}} + M_{\text{support}} \times Cp_{\text{support}} + M_{\text{supportpowder}} \\ \times Cp_{\text{supportpowder}}) \times \Delta T \end{aligned} \tag{9}$$

$$E_{\text{maintain}} = \frac{S_{\text{oven}} \times \left(T_{\text{mean}} \times t_{\text{increase}} - \sum (T_{\text{maintain}} \times t_{\text{maintain}})\right)}{R_{\text{furnace}} + \frac{1}{h_{\text{int}}} + \frac{1}{h_{\text{ext}}}} \tag{10}$$

Idle state energy

The main source of energy consumption of the printing has been found to be the idle state energy consumption, consisting of computer consumption (60 W), lighting consumption (12 W), and other sources such as controllers (50 W). These elements are running during the entire printing process which explains their importance in the general energy consumption of the machine.

Others

Experiments have shown that all the other component's energy consumption represents less than 1 % of the total energy consumption. These components are, however, included in the model in view of further studies, but are not described in this chapter.

Material consumption models

Print with binder

Because of its viscosity characteristics, binder has to be washed out of the system frequently. These cleanings are made every two layers with the M-Lab machine.

The binder and cleaner consumption are therefore linear with the number of layers:

$$M_{\text{binder}} = \frac{\rho_{\text{binder}} \times Vb_{\text{layer}} \times H_{\text{part}}}{H_{\text{layer}}} \tag{11}$$

$$M_{\text{cleaner}} = \frac{\rho_{\text{cleaner}} \times Vc_{\text{layer}} \times H_{\text{part}}}{H_{\text{layer}}} \tag{12}$$

Powder

In this study, all the powders used in the process but not printed are considered reusable because unused powders are combined with new powders for new rounds of printing. No significant mechanical property change has been observed when old and new powders are used together. The overall amount of reusable powder is therefore the mass of powder used to fill the supply system minus the mass of the part.

Once the binder jetting AM process is modeled in the UMBERTO NXT LCA system, the LCI data can be calculated with defined reference unit and reference flow. Then some inventory databases such as Ecoinvent v3 (Weidema et al. 2011) can be used for secondary material and energy consumption evaluation such as powder manufacturing and binder manufacturing. Based on the LCI data, some indicators such as ReCiPe midpoint (Goedkoop et al. 2008) are chosen to assess the environmental impact generated through the manufacturing processes. The environmental impact result is the output at the end of the proposed design method.

4 Case Study

In this section, a case study is provided to illustrate further the proposed design methodology. In this case study, a triple clamp of a motor cycle is used. The original design of this product is shown in Fig. 19.

To redesign this product, the functional specification and design requirements are first summarized. The primary function of a designed triple clamp is given below:

Function 1: To connect steering handle and front fork with motorcycle frame (shown Fig. 20). This connection can transfer torque from the steering handle to the front fork which allows the front fork to pivot from side to side.

The design requirements of a designed triple clamp are also listed below:

Design Requirement 1: The solid connection should be achieved by a designed product, which means a triple clamp does not fail or break during its working state.

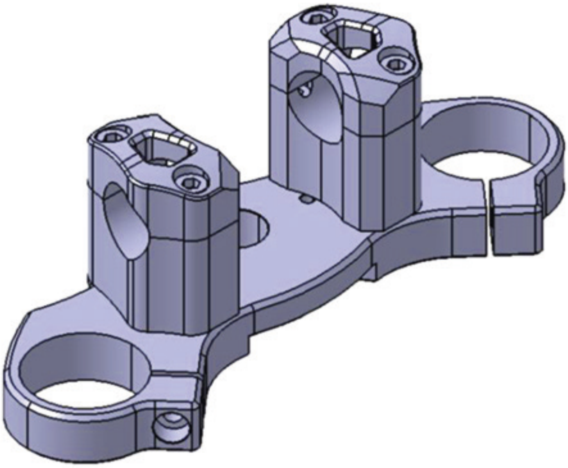


Fig. 19 Triple clamp of a motor cycle

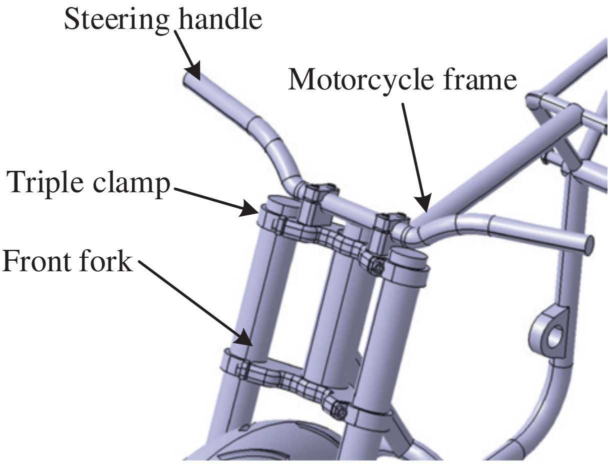


Fig. 20 Primary function of a triple clamp

Design Requirement 2: The connection should be stiff and rigid enough, which means the maximum deflection of a design triple clamp should smaller than a given value.

Based on the input functional specification and design requirements, the proposed design methodology is applied to redesign this triple clamp during the functional design stage, because the primary function of a designed product is easy to achieve. Thus, the functional entity can be directly obtained from the primary function of a triple clamp without a functional decomposition process. The

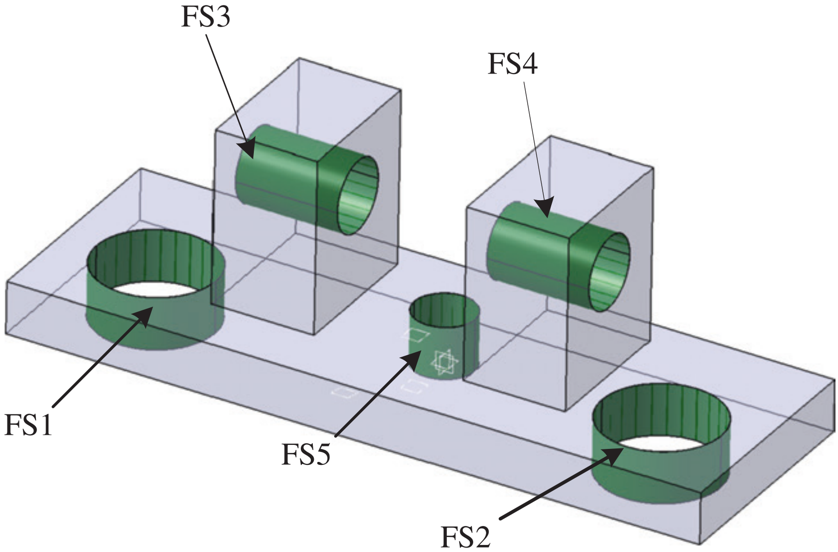


Fig. 21 Physical entity of a triple clamp

functional entity obtained at the end of functional mapping step is defined as a solid structure which can connect the front fork and steering handle with the frame of the motorcycle. Based on the functional behavior described above, the physical entity of a triple clamp is build. The FSs and FVs of this physical entity are shown in Fig. 21.

This physical entity has five FSs in total. Among them, FS1 and FS2 are the assembly surfaces for the connected front fork. FS3 and FS4 are the assembly surfaces for the steering handle. FS5 is used to connect to the frame of motorcycle. It should be noted that all five FSs of this physical entity are fully constrained with zero DDoF, because they should fit their connected components and implement the functional behavior defined by the related functional entity. The FV of this physical entity is generated, only representing the design space of FV. As mentioned in Sect. 3.2, the specific shape of this FV cannot be decided in the current step. In this case study, the redesigned product is planned to be fabricated by the AM process. In order to take the unique capability of the AM process which can fabricate parts with complex geometry, the FV of this physical entity is represented by the voxel-based parametric modeling method. The DDoF of this FV is equal to the number of voxel points needed to represent the design space of an FV. For this case study, the size of the voxel point is chosen as 3 mm according to the dimension of an FV.

Besides the geometrical shape of a designed physical entity, the material of this physical entity also needs to be determined. In this design case, stainless steel is used for the original design. This material can also be used for a redesigned product. However, the mechanical properties of printed stainless steel may be slightly

Table 5 Mechanical properties of printed stainless steel fabricated by a binder jetting process

Material	Elastic modulus	Ultimate strength	Density	Yield strength
Stainless Steel 316 infiltrated with bronze	148 GPa	407 MPa	7.86 g/cm^3	234 MPa

different from the properties of the stainless steel fabricated by traditional manufacturing processes such as milling. For this case study, the redesigned product is supposed to be fabricated by a binder jetting process. Some basic material properties of printed stainless steel 316 are listed in Table 5 (E. Inc 2014). These properties are used in the design optimization stage, which is discussed in the following paragraphs.

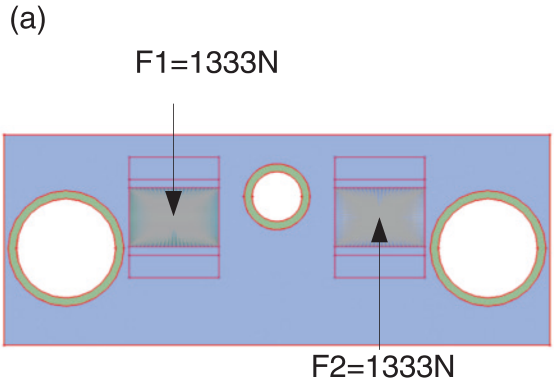
For this case study, there is only one physical entity which serves for one functional entity. Thus, the physical integration is no longer needed. After the functional design stage, the physical entity shown in Fig. 22 can be output for the design optimization stage. In the design optimization stage, the feedback of environmental impact evaluation needs to be calculated first. According to the energy and material consumption model described in Sect. 3.5 for the binder jetting process, there are two design-dependent parameters. They are part volume V_{part} and height of a part h_{part}. As to the height of a part, it is almost constrained by the position relationship of FSs. For this design case, the DDoF of FSs is equal to zero. Thus, in this design process, the volume of the designed product is regarded as the design target. By analyzing the environmental impact model, the minimal environmental impact can be achieved when the design-dependent parameter V_{part} equals zero. Thus, the $p_{\text{design}}{}^{*}$ can be determined as below:

$$p_{\text{design}}{}^{*} = \left(V_{\text{part}}\right) = (0) \tag{13}$$

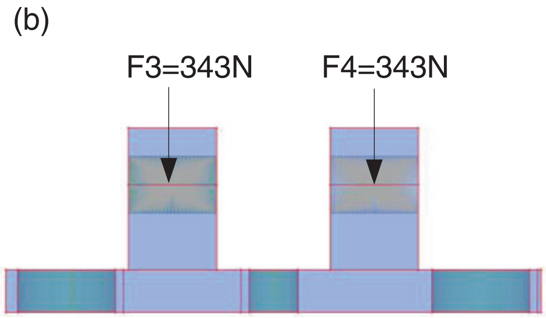
After determination of the design objective, the topology optimization method is used to update the relative density for each voxel point in FV to obtain the final design result. In the topology optimization process, two different load cases (shown in Fig. 22) are considered based on the existing literature (Kumar and Choudhary 2015) for the triple clamp design. Load case 1 is the steering torque applied on a triple clamp. Load case 2 is the vertical impact force applied on a triple clamp. For both load cases the FS1, FS2, and FS5 are constrained with six degrees of freedom.

Besides the boundary conditions discussed above, in the topology optimization process the thin layer of material should be kept around the mentioned FSs for assembly purposes. Thus, thin layers of material around FSs are denoted as non-design space for topology optimization. The thickness of these thin layer material is 2 mm for this design case. The design space and non-design space of this case study are shown in Fig. 23.

Fig. 22 Load condition of a designed triple clamp

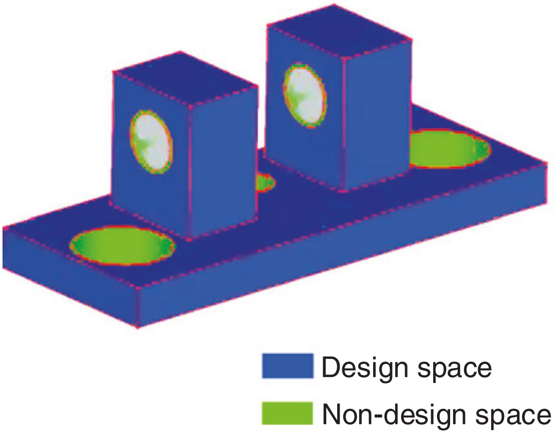


Load case 1



Load case 2

Fig. 23 Design space of topology optimization



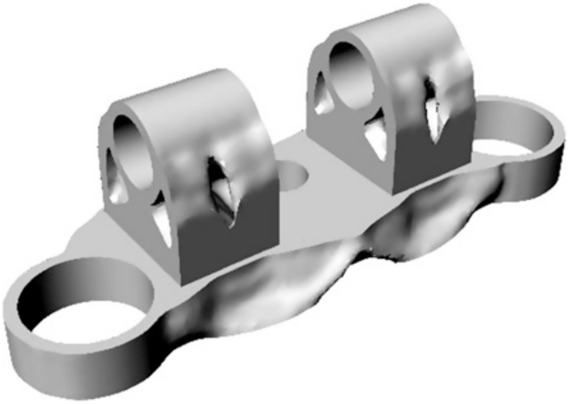


Fig. 24 Result of topology optimization

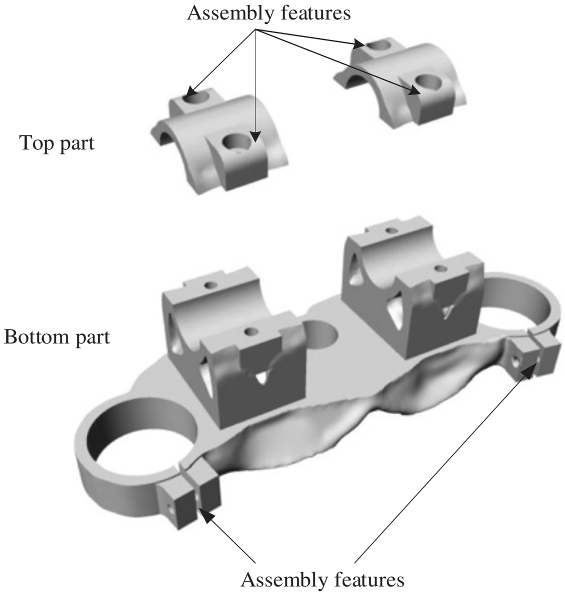
The objective of topology optimization is the overall stiffness of a designed product rather than product volume. Thus, a sequence of product volume fraction is generated first. In this volume fraction sequence, the volume fraction ranges from 10 % to 100 % at 10 % intervals. The elements in this volume fraction sequence are regarded as the constraints during the topology optimization. Besides volume fraction constraints, the yield strength of printed stainless steel is also regarded as a design constraints during the optimization process because of the Design Requirement 1 mentioned above. The topology optimization problem is solved by OptiStruct solver (Engineering 2009). Based on the algorithm described, the minimum volume fraction of a designed triple clamp which can satisfy all design requirements is found to be 40 %. The optimized result under this volume fraction constraint is shown in Fig. 24.

After the design optimization step, design refinement is needed to smooth the boundary of FV obtained from the last design stage. Moreover, the assembly ability also needs to be evaluated. It is difficult to assemble the steering handle to the triple clamp with the current design shown in Fig. 24. To ease the assembly process, the original design is broken down into two sections with three parts. Moreover, some assembly features are also added in the optimized design. The result of the design refinement stage is shown in Fig. 25.

At the end of the design process, the environmental impact evaluation model is applied to the obtained design. To compare this value with its original design, the environmental impact factor of the original design is also calculated based on the environmental impact evaluation model of the milling process from UMBERTO NXT LCA software. For comparison, the following information is kept the same:

1. The scope of the LCA study is to compare the environmental impact of different design solutions generated based on functional design methods. It is also in the scope to compare the environmental impact of different manufacturing methods specifically between the conventional milling process with the binder jetting AM process. The function unit is a single design product. The reference flow is the required service life expectancy. Different design solutions all have the same expected service life expectancy.

Fig. 25 Result after design refinement



2. Assumptions are made in the LCA study. It is assumed that the conventional CNC milling process is a representative manufacturing method to fabricate the design solutions. All features of the design can be successfully machined without failure. It is also assumed that the binder jetting process is able to manufacture the design solution successfully without failure.
3. The boundaries of this LCA study are set only to consider the electricity needed for the chosen function unit and reference flow; the environmental impact produced from manufacturing electricity generation equipment is cut out. The environmental impact produced from binder jetting manufacturing and conventional CNC machines are also cut out.

The comparison between the original product and the optimized product is made. In this case study, the ReCiPe midpoint indicator is used to analyze quantitatively the environmental impact of the designed products. Some of the major ReCiPe midpoint indicators obtained from the environmental evaluation model are shown in Table 6. It is clear that the redesigned product has less environmental impact than that of its original design fabricated by traditional manufacturing processing. Moreover, the overall parts count of a designed product is also reduced. A comparison of the parts count between the original design and the optimized design is shown in Table 7. It is obvious that the proposed design methodology can help designers to reduce the overall parts count, which can also make a contribution to less environmental impact and less cost.

The proposed case study discussed in this section shows the unique capability of the proposed sustainable design methodology. It is clear that by redesigning

Table 6 ReCiPe midpoint of the designed product

	Binder Jetting	Milling
Agricultural land occupation	0.77 m^2	1.77 m^2
Climate change/CO_2	3.13 kg	30.72 kg
Fossil depletion	1.68 kg	6.24 kg
Freshwater ecotoxicity/FETP100/1,4-DCB-Eq	0.01 kg	1.44 kg
Human toxicity/1,4-DCB-Eq	0.06 kg	3.06 kg
Ionizing radiation, IRP_I/U235-Eq	0.16 kg	1.96 kg
Marine ecotoxicity/1,4-DCB-Eq	8.81E−3 kg	1.33 kg
Marine eutrophication, MEP/N-Eq	3.88E−3 kg	0.06 kg

Table 7 Comparison between original design and optimized design

	Parts count (including assembly bolts)	Volume/cm^3
Original design	13	$4.14e10^2$
Optimized design	7	$3.44e10^2$

the existing product with the proposed design methodology the environmental impact of product's manufacturing process can be significantly reduced. The reduction is mainly because of the AM-enabled design method, topology optimization, used in the proposed design methodology. Moreover, the overall part count is also decrease from 13 to 7. Generally, by taking the advantage of the AM process, the proposed design methodology in this chapter enables designers to minimize the product's environmental impact of its manufacturing process as well as to reduce further its overall parts count through functional integration and parts consolidation.

5 Summary

In this chapter, a sustainable design methodology for the products fabricated by AM process is discussed. First, the current state of research progress on sustainability study of AM process is briefly reviewed. It is obvious that most current research focuses on the sustainability of the manufacturing process but neglects the impact from the design stage. The unique capabilities of the AM process may bring more freedom on the design stage, which may further improve the sustainability of a designed product and reduce its environmental impact during manufacturing stage. Thus, this chapter aims to provide a general sustainable design methodology for AM processes. To introduce this general design methodology, those AM-enabled design methods are first reviewed. Based on the existing AM-enabled design method, a general sustainable design methodology for

AM processes is proposed and discussed in detail. Finally, a brief case study is provided to illustrate and validate the proposed design methodology. Generally, the proposed design methodology can reduce the product's environmental impact during the manufacturing process by optimizing the design-dependent parameters which may cause the major environmental impact. Moreover, the parts count can also be reduced through functional integration and physical integration steps in the proposed design methodology. The reduction of the overall parts count definitely decreases assembly difficulties and further minimize the products' environmental impacts. It should be noted that the proposed design methodology also has certain limitations. For example, current design methodology only considers the environmental impact of the manufacturing process. However, sometimes, the environmental impact of products during other major life cycle phases may play an even more important role. For example, the weight of an aircraft may not only affect its environmental impact during the manufacturing phase but also has a great effect on its service phase. The lower the part weight the less fuel it uses. Thus, this proposed design methodology needs to be extended to the full product life cycle in the future.

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