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Design for manufacturing to design for Additive Manufacturing: Analysis of implications for design optimality and product sustainability

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Abstract

In response to the development of new materials, improved design methods, and increased societal demands to manufactured products, Design for Manufacturing (DfM) concept has paved the way to incorporate these demands into the development of more sustainable products. However, the emergence of Additive Manufacturing (AM) techniques has brought new manufacturing capabilities that are beyond the conventional DfM concept. For this reasons there is a need to rethink design considering the capabilities of these technologies and make smooth transition from design for manufacturing to design for Additive manufacturing (DfAM). In this paper, the possible paradigm shift from DfM to DfAM is analyzed, the impacts on the realization of optimum design, and accommodation of the requirements for product sustainability is assessed. The role that DfM played in previous approaches to product development process and the factors that are the drivers of the DfAM approach are also discussed.

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Keywords: design for manufacturing; design for additive manufacturing; design optimization; topology optimization; product sustainability

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1. Introduction

The development of new materials, improved design methodologies and knowledge based societal demands that appeared in the last decades have enabled the concept of Design for Manufacturing (DfM) to pave the way to incorporate the above-mentioned concepts in the product development or design process. The DfM concept can be defined as design of a product with consideration of manufacturing knowledge throughout the product development process. The main goal of DfM is reducing manufacturing cost and improving product quality [1] by addressing the manufacturing constraints. Parallel with the DfM efforts, designers should also address the issue of optimum design that is demanded by diverse applications. This can be considered as one of the design engineers' paradox. Optimum design is a design process of searching a compromise between the size, shape or topology of a part and utilization of as minimum as possible material while ensuring the overall performance of the part. Optimum design is not fully realized in conventional manufacturing techniques such as turning and milling as they have limitations on manufacturing of complex part geometries [2]. Contrary to the conflict between DfM and design optimization in the conventional manufacturing approach, where not all optimized features can be manufactured, the AM approach, in a way, realizes design optimization. Additive manufacturing is a process of joining materials to make objects from 3D model data, usually in a layer-by-layer process opposed to subtractive manufacturing [3, 4].

Nowadays, a global effort is emerging to implement AM technology in both fabrication of diverse consumable materials and other sectors such as medicine [5, 6]. Among others, this move is expected to remove the huge manufacturability constraint because complex geometry is no longer an issue of the design engineer. In addition to its capability of building complex geometries, it also has other potentials such as building hierarchically structured parts, multi-materials in a single part manufacturing and functionally integrated objects [7]. These capabilities of additive manufacturing makes further move from the conventional optimization for manufacturability to optimization for functionality, enabling parts to have higher performance. Furthermore, the need of the customers for long lasting and environmentally friendly product is dramatically increasing, as the concern of sustainability in all products and services is a current worldwide concern. To cope with this issue, designers are developing and using different approaches to account for product sustainability into the product development process. Sustainable product can be defined as 'a product that gives as little impact on the environment as possible during its life cycle' [8]. Thus, sustainable product design is the product development process in which the environmental issues are accounted for at all stages of the product development phase.

This review article will focus on assessing the possible natural paradigm shift from design for manufacturing to design for additive manufacturing (i.e. transition from DfM to DfAM). It also analyses the implication of design optimality and product sustainability in product development process in the conventional DfM concept and in the emerging DfAM concept. This kind of analysis simplifies the transition from DfM to DfAM for the design engineers and for the product development team at large so that they can benefit from the unique capabilities of additive manufacturing technologies.

The paper is organized as follows: first general information about design for manufacturing concept and its role in product development process are discussed in Section 2, which emphasizes the past and current developments. In Section 3, the need for transition from DfM to DfAM is elaborated followed by Section 4 that discusses the implication of design optimality and then product sustainability in design for additive manufacturing is presented in Section 5. Finally, concluding remarks are given in Section 6.

2. Design for manufacturing

For a long time in the history of product development process, the two broad concepts design and manufacturing were thought separately. As a result, it was very expensive to correct the failure encountered during the product development process later in the manufacturing phase. However, with the introduction of computer-based technologies and the emergence of concurrent engineering approach in the field, design and manufacturing are no longer separate but interrelated in one way or the other, as one cannot sustain alone. In order to ease and make the manufacturing process sustainable, the knowledge and experience of different manufacturing concepts and techniques should be incorporated in the product development process and this is done with design for manufacturing approach. To get the maximum benefit from DfM concept, general guidelines [9] with consideration of conventional manufacturing techniques are developed from previous experiences in the area. In addition to these general design guidelines, there are specific guidelines that have to be considered when it comes to specific manufacturing processes.

The role of DfM in product development has become very immense due to several reasons including the fact that

- the products are getting more complex,
- the market competition of similar product is very high,
- wide variety of end users are available,
- the existence of needs for large number of products and
- consistent high quality expectations [10].

To cope with the above listed reasons, the concept of DfM has to be implemented in every industrial manufacturing companies. Considering the manufacturing constraint early in the product development process to reduce the manufacturing difficulties improves the performance of the product and reduces the cost drastically since manufacturing errors are avoided in advance. As an achievement of DfM approach, when new products are compared with earlier once, it is eminent to find (a) fewer parts, (b) new materials, (c) integrated and customized parts, (d) compact standard parts and subassemblies, and (e) simpler assembly procedures [11]. All these efforts are made to show the close relationship between manufacturing and design thus enhance the role of DfM in product development process.

3. Why design for additive manufacturing?

Though its initial inception was for design visualization and rapid prototyping [12], the 3D printing technology is progressively developing to a commercial manufacturing method with a capability of printing end user products from diverse materials including metallic parts [13, 14]. This is an industrial breakthrough in manufacturing technology and has many benefits that are not realized in conventional manufacturing techniques. In addition to the capabilities listed in Table 1 [7], there exist many others such as mass customization, personalization of products and decentralization of production [21, 22] that provide benefits by opening new design space that cannot be fully utilized with conventional DfM.

Design guidelines, design principles and design rules have been reported [7, 23, 24] for parts manufactured using additive manufacturing. These guidelines, principles and rules are paving the way to a new DfM concept, DfAM to benefit from the unique capabilities of the technologies [25].

Table 1. Unique capabilities of AM

Capabilities	Description
Shape complexity	It is possible to build near net shape [15], complex shape geometry and interconnected internal channels [7] that are not feasible with conventional manufacturing techniques.
Material complexity	Materials can be processed one point, or one layer, at a time as a single material or as a combination of complex compositions of materials [16] so that different properties can be observed in different locations of a single product because it is possible to alter physical, chemical, biochemical or mechanical properties locally [17].
Functional complexity	Fully functional devices [18] not just individual piece-parts can be produced in one build as the technology permits the consolidation and functional integration of parts [19]. Functional integration of parts reduces part count thus reducing difficulties encountered during assembly process.
Hierarchical complexity	Features can be designed with complex shapes across multiple size scales. Internal structure [18] can be changed using cellular structures [20] such as honeycombs, foams, or lattices [15], to fill certain regions of a geometry. This increases a part's strength to weight or stiffness to weight ratio so that excess use of materials is avoided thus cost is saved.

The aim of DfAM is defined as 'Synthesis of shapes, sizes, geometric mesostructures, and material compositions and microstructures to best utilize manufacturing process capabilities to achieve desired performance and other life-cycle objectives' [26]. In this regard, few attempts have been made in the last ten years to develop methods that consider these unique capabilities of the technologies. AM enabled design method is developed [27] with a focus on downstream design stages to integrate process knowledge and structural optimization in order to reduce part count and improve product performance. A framework of methodologies for DfAM based on traditional design process [28] to make the adoption easy for the design engineers, who are used to the conventional design process, is also another contribution. A benchmark design framework for assembly level DfAM that utilizes functional integration, part consolidation and design optimization [29] is also proposed. Even though, the feasibility of AM to replace the existing manufacturing processes is still the subject of future studies, the breakthrough in manufacturing is yet to be followed by a breakthrough in designing process [30]. Since the efforts mentioned are relatively new and are not covering the whole life cycle of products, universal and standardized design for AM method has to be developed so that the team of product development process could employ it throughout the globe.

4. Design optimality in additive manufacturing

Design optimization is a design process in which an objective function subjected to performance constraint is maximized or minimized iteratively by changing design variables such as part dimensions, geometries, material properties and so on in order to come up with an optimal design [31, 32]. Design optimization is a broad topic that makes collective use of computer-aided design (CAD) and finite element analysis (FEA) with the consideration of manufacturing processes. Though structural design optimization has started long time ago with consideration of the existing manufacturing techniques, the existing manufacturing techniques did not sufficiently benefit from this design approach because of manufacturing constraints. This means the optimized design could not be produced with the existing manufacturing techniques, as there were limitations on product complexity, size (how much small) and topology. These types of questions seem to be answered with AM technologies because they eliminate or reduce design and manufacturing restrictions previously existed. Furthermore, the use of design optimization approach with AM can save much time, material and energy that are not economically achievable with any other processes.

Design optimization can also be considered in redesigning already existing products to reduce their weight and modify their topology while maintaining the functional requirements as illustrated in Figure 1 [23]. This concept of using design optimization has been reported in a number of recent works. For instance, redesign optimization and additive fabrication of an antenna support arm for space satellite performed by OptiStruct and Altair Product Design teams at Altair Engineering showed a weight reduction of 50% [33]. An airplane bracket with reduced weight was redesigned through topology optimization and manufactured using laser additive manufacturing [34]. These kinds of geometries are very difficult to manufacture using the traditional techniques but they are achievable with additive manufacturing. Designers at ARUP in Netherlands have explored the opportunity of combining design optimization and additive manufacturing to redesign steel node for a tensegrity structure [35]. In their research, they found out that the combined design optimization with additive manufacturing could enable to reduce the weight of the node by 75 % without decreasing its functional and structural performances.

Another area of application of design optimization with AM is in the medical sector, where the approach is used to develop personalized implants for specific patient with special features. Selective Laser Melting (SLM) is used to produce a metallic hip endoprosthesis implant with an osseointegrative surface with special lattice structure that can allow the bone ingrowth and avoid the phenomenon of stress shielding [36]. Porous structures for different medical implants can also benefit from both design optimization and additive manufacturing. Porous titanium implant with 60% porosity was fabricated with Electron Beam Melting (EBM) additive manufacturing technique for a person with a defect caused by trauma or disease process [37]. These kinds of implants are patient specific, can be large or small based on the defect area and the size of the skull of the patients and it could be difficult to find personalized implants with the defect size. Moreover, it is demanding to realize such a porous implant that can allow the ingrowth of bone and cells if design optimization and AM were not implemented simultaneously in the design process.

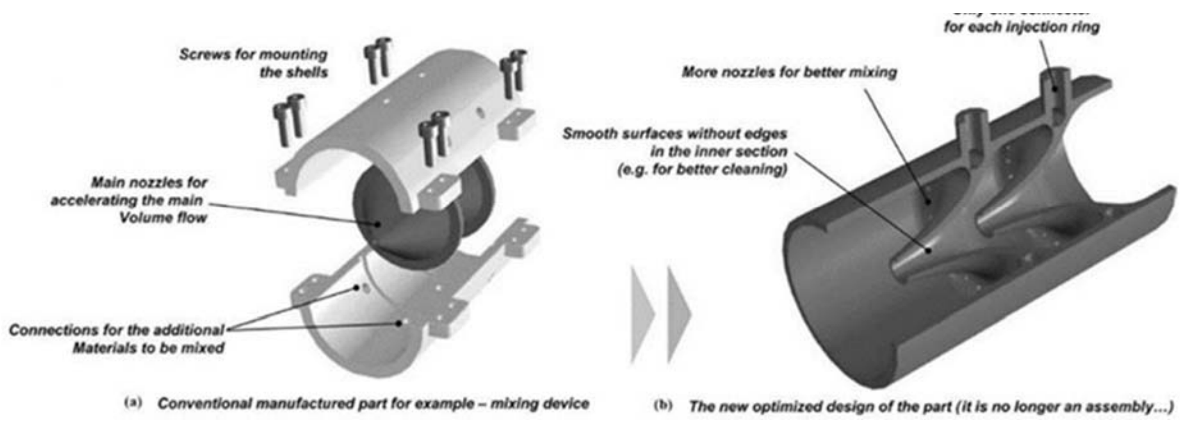

Fig. 1. Redesigning an assembly to take the advantage of rapid prototyping process

To cope with the developments in AM for fabrication of parts, significant progresses are also observed in developing topology optimization tools [38, 39] integrated with computer-aided design (CAD) tools. An investigation carried out on twenty conventional commercial and educational software tools showed that all the commercially available topology optimization software packages have similar potentials and relatively more functional than educational once [40]. They also pointed out that the current commercial software does not provide sufficient manufacturing limitations to remove the necessity of manual interpretation of results for AM. Regarding the development of software for topology optimization, AM technology specific tools have to be researched and developed as different AM machines have different capabilities and different processing techniques.

5. Product Sustainability in additive manufacturing

With the dramatically changing world, sustainable product development is a hot issue as the world is becoming warmer than before because of the increased use of fossil fuel. To deal with this problem in every aspect of life and to make our planet stable and comfortable, the product development, production and consumption have to be sustainable. The concepts of design for sustainability and sustainable production are directly related to sustainable product. Design for sustainability is the product development process in which the social, economic, environmental and institutional aspects are taken into consideration at all stages of the design process [41]. However, the awareness and understanding of the design engineers about the product's social, economic and environmental aspect is very limited in the conventional design process [42]. The Lowell Center for Sustainable Production (LCSP) at the University of Massachusetts Lowell has defined sustainable production as 'the creation of goods and services using processes and systems that are non-polluting, conserving of energy and natural resources, economically viable, safe and healthy for workers, communities, and consumers, socially and creatively rewarding for all working people [43]. Different frameworks and tools reported elsewhere [44, 45] are developed to realize sustainability in product development process using conventional manufacturing techniques.

The available methods for developing sustainable products or assessing sustainability of products produced by conventional manufacturing systems can be extended to additive manufacturing. However, since these methods are too many, in-depth evaluation of the advantages and disadvantages of each of them is required as it can lead to a decision that cannot guarantee sustainability rather worst the product [46]. Integrating these methods could also be much useful as they can complement one another with their respective potentials. A comparative life cycle assessment (LCA) study [47] for plastic materials made on two additive manufacturing (fused deposition modeling (FDM) and polyjet printing) and traditional computer numerical controlled (CNC) machining shows that the sustainability of AM depends primarily on the percentage of utilizing the machine. They found out that FDM machines have the lowest ecological impact per part over both CNC machine and polyjet machine. In contrast to this study, another similar comparative LCA analysis conducted using an EcoIndicator 99 method [48] shows that CNC machining has less ecological impact than AM technologies (FDM and selective laser sintering (SLS)). The conflict in these studies are evidences for less research efforts in this regard and more has to be done in the future to assess the sustainability of AM using different methods. A review study on sustainability of direct metal additive manufacturing (DMAM) showed its sustainability with regard to

(i) redesign of products,
(ii) efficiency improvement of manufacturing process and
(iii) repair, remanufacturing and life extension of products [49].

A comparative study is carried out on the environmental aspects of direct metal deposition (DMD), additive manufacturing technique and conventional manufacturing for die and tool manufacturing [50]. The study showed that DMD has greatest opportunity to reduce cost and environmental impact of the parts that could be resulted from the remanufacturing ability of the technology.

There are researches going on to enhance the sustainability of AM systems as these technologies are in promising progress for the future of manufacturing. A study proposing a computational tool called Design for Environment (D4E) for the assessment of the sustainability of FDM demonstrated its applicability using different case studies revealed that part build orientation is a critical factor for the energy consumption during production [51]. Another research demonstrated the use of heusristic-based optimization techniques in additive manufacturing industries in terms of assessing material wastage and energy consumption to optimize process plan and improve sustainability of the process [52]. A sustainability issues analysis on SLS technology pointed out that the current SLS technology is not energy efficient and proposed application of better thermal management, elimination of powder heating and using high efficiency laser that could significantly save energy [53]. A research conducted at the University of Exeter pointed out that the use of lightweight material structures, thermite material systems and personalized processing as potential sustainability enhancement methods that could reduce material and energy consumption in AM [54]. A new methodological model that takes into account all aspects of AM processes; electric consumption, material consumption and fluid consumption is also developed for evaluating AM processes life cycle assessment [55]. Furthermore, a framework that integrates design optimization with LCA in the design stages is proposed [56] as depicted on Figure 2. The proposed framework facilitates the evaluation of environmental impact of a product early in the design phase so that the product with minimum impact could be obtained prior to the manufacturing stage. In this framework, first the product is optimized for sustainability through topology optimization. Then, the design is forwarded into the energy and consumption models, which are special process models for specific AM processes, respectively for the estimation of energy and material consumptions based on the design. The energy and material data are compiled as life cycle inventory (LCI) and then further analysis is made through life cycle impact assessment (LCIA) to get the estimation of environmental impact of the optimized design. If the estimation is not satisfactory, other rounds of optimization will be done and then assessed for the impact until it gets to a level that is acceptable for sustainability of the product.

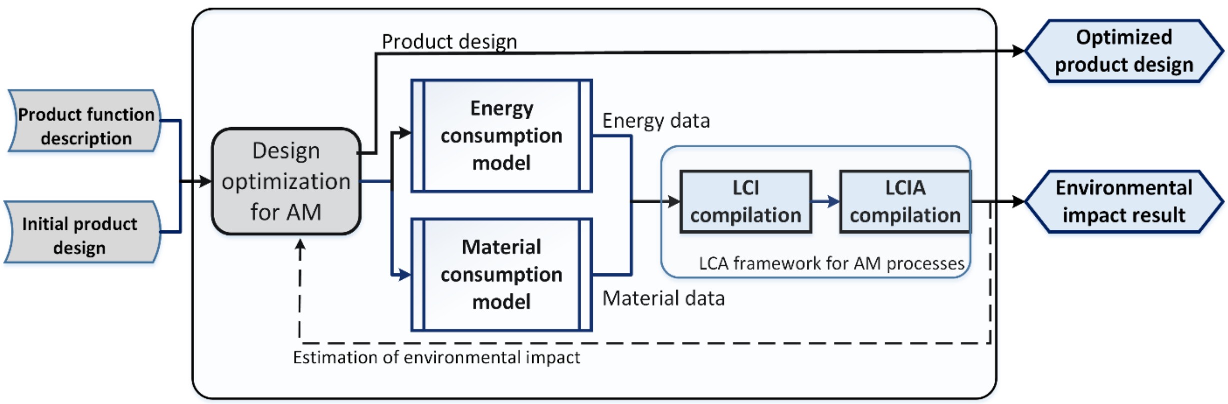

Fig. 2. Illustration of a general framework for evaluation of environmental impact evaluation of AM processes.

6. Conclusions

From the perspective of the emerging AM technology, the natural transition to DfAM and the design issues to be considered in this regard are investigated and reported in this article. From the comparative assessment carried out on the implication of design optimality in additive manufacturing and conventional manufacturing, it can be concluded that unlike conventional manufacturing AM is synergic with design optimization to develop products with better performance and lightweight than the once produced by conventional techniques. Concerning the sustainability of products, the analysis shows that the technology is on a promising progress with better achievements than conventional manufacturing techniques. However, since AM is in its infancy, there are still a number of challenges that need to be overcome to realize the full potential of the technology. From the assessment carried out, it can clearly be observed that the developed DfAM methodologies for the realization of optimal design and product sustainability are relatively new and not yet standardized and there are still gaps that need further investigations. The goal of this study is also to use the identified potential research directions in developing design procedures for additive manufacturing of functional parts with focus on realization of topology optimization for additive manufacturing.

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