Form and Function: Functional Optimization and Additive Manufacturing

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Abstract. In these last years, with the advent of Additive Manufacturing, a deep review of the design methodologies has occurred. This is mainly due to two reasons: the technological progress and the new manufacturing capabilities that offer designers much greater freedom for the creation of complex geometries; the modern engineering optimization tools that are spreading widely in the industrial design field, and offer new opportunities for searching a compromise between form and function. On the basis of these two reasons, the paper presents some reflections and exemplifications on the changes that new AM technologies, together with the optimization tools, are bringing in the design process.

Keywords: Additive manufacturing · Design theory and methodology · Topology optimization

1 Introduction

In the product design, the antinomy between form and function has always existed, a long-running diatribe that has been over-simplified and polarized into the atavistic quarrel between architects and engineers.

This antinomy arises from the fact that the form belongs to the perceptible unmeasurable world, whereas the function to the rational measurable one. While the form addresses the aesthetic, perceptive and emotional expressions, on the contrary, the function refers to the rationality, technique, and performance.

In the industrial design field, this dichotomy never existed: form and function have always been of equal relevance and importance, and from antithetical become complementary terms. In the development of design products, in fact, form and function are tightly related and closely interlinked to each other. This is demonstrated by the fact that successful industrial products on the international market feature both high aesthetic and functional qualities.

Although the ultimate goal of designers is to achieve an optimal balance between form and function, the design process is affected by the instruments and tools that support designers' work and by their experience and consolidated knowledge. In fact, the tools and systems, traditionally adopted in the design process, on the one hand, support and simplify the designer work, but, on the other hand, could influence the design process and put some limits to the designers' creativity. This is quite evident in the traditional design process, which starts with the definition and modeling of the

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geometry of the product, and follows with its functional analysis and technical feasibility. Then, as far as form and function have the same importance, in the practice, products are developed with function as a primary consideration but according to a form-to-function approach. As above mentioned, this is essentially due to the tools and systems that support designers' work which require a geometric model to proceed with the functional simulation and analysis.

On basis of the abovementioned considerations, it is quite evident how Additive Manufacturing (AM) represents a radical change not only from a technological point of view but also because it enables designers to rethink the overall product development process and revolutionize their approach to design.

Although AM was originally referred to a novel class of manufacturing processes for rapid prototyping applications, it has rapidly evolved in flexible and reliable technologies for end-use part production and tooling a variety of materials, including metals. This has been an industrial breakthrough in manufacturing technology thanks to its capabilities to overcome the technological limitations and constraints imposed by conventional manufacturing techniques.

In the last few years, in response to the development of AM techniques, a variety of design theories and methodologies (DTM) based on AM has emerged, therefore entailing and supporting a smooth transition from Design for Manufacturing (DfM) to Design for Additive Manufacturing (DfAM). The AM revolution, in fact, on the one hand, has led to a greater freedom and a higher number of solutions in the product design. But, on the other hand, it required both a radical re-think of the current best practices for product design and the development of new design paradigms [1].

On this subject, the paper presents some reflections and exemplifications on the changes and implications that the new AM technologies, coupled with the engineering optimization tools, are bringing in the product development process. In fact, its huge capabilities open up a multitude of potential design approaches, ranging from traditional ones to completely new methods and techniques. In this regard, starting from the current DfAM concept and definitions, two radically different design approaches are discussed. The first one focuses on designers' creativity and their greater freedom for the creation of complex geometries that were unimaginable before the advent of AM. The AM technologies, in fact, encourage designers and engineers to go beyond the conventional thinking tailored to the capabilities of traditional manufacturing methods and push them toward a "*form-driven design*" approach that unlocks their imagination for creating innovative designs. On the other hand, the second one exacerbates the "*function-driven design*" approach by focusing on the functional properties of the product and postponing a detailed and accurate definition of the geometry in the last stages of the design process.

2 Traditional Method

Design methodologies and tools provide an effective way to rationalize the design and production processes, foster and guide the abilities of designers, encourage creativity, and at the same time drive home the need for objective evaluation of the results. Thanks to these methods it is then possible to structure the design activities in a purposeful way that forms a clear sequence of main phases and individual working steps so that the flow of work can be planned and controlled. According to a traditional design approach, the design process consists of three main phases: concept design, embodiment design, and detail design.

As above mentioned, designers then start a design process by defining design goals and planning a sequence of activities and tasks that, in practical terms, are influenced by the tools and instruments that they use. In fact, the tools and systems, that are traditionally adopted in the design process, on the one hand, support and simplify the designer work, but, on the other hand, prioritize some activities and goals that drive design creativity.

The following Fig. 1 shows the traditional design method as it evolves from the concept to the physical prototyping stage. In order to verify the functionality and feasibility of the product, the CAx tools require a geometry as input. This entails that the design process starts in the conceptual stage by developing the functional specification, over the user needs, that are then immediately translated into geometric shapes by means of a CAD system.

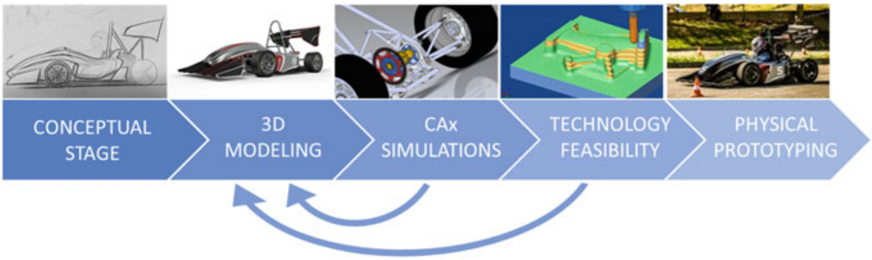

Fig. 1. Traditional design approach

On the basis of these considerations, it is possible to agree on two points. Firstly, the traditional approach starts by working on the geometry in order to give form to a function. Secondly, the iterative process that occurs between the modeling stage and the simulation analysis is crucial for the development of a successful product that puts the emphasis both on the aesthetical and functional aspects.

3 Design for AM

Because of the technical and economic properties of a product, and the commercial importance of timely and efficient product development, it is of fundamental importance to have a well-defined design procedure that guides and supports designers to find optimum design solutions by addressing the given design requirements and manufacturing constraints.

The AM revolution has led to a rethinking of the current design best practices and the development of new design paradigms [1]. Furthermore, in order to get the maximum benefit from the potentials offered by AM technologies, a natural paradigm shift has occurred from DfM to DfAM.

The purpose of DfAM is a "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" [2]. DfAM is the set of methodologies and tools that help designers to take into account the specificities of additive manufacturing (technological, geometrical, pre/post-processing, etc.) during the design stage [3].

Graziosi et al. [4] highlight (through the description of the re-design activity performed using the software tools currently available on the market) the number of heterogeneous aspects that need to be taken into account when designing for AM in order to fulfill all the functional, technical and manufacturing requirements. The aim is to use the acquired experience to reflect on the possible strategies to put in place for a better synthesis of the functional and process-based aspects.

In [5], the authors propose a complex DfAM framework for designing end-use components and products. The proposed framework has been developed on the basis of information collected by means of personal interviews occurred with designers and AM professionals that have great experience in product design oriented to AM.

Particularly significant are the works that show topology optimization (TO) applications in the AM field. In [6] the authors present two customer cases with the goal of redesigning existing products for manufacture with SLM. In [7], a benchmark design framework for assembly level DfAM that utilizes functional integration, part consolidation, and design optimization is also proposed. Doutre et al. [8] compare different possible approaches to generate a CAD model from topological optimization analysis results. An exhaustive bibliography of AM-related structure design optimization methods is presented in [9]. In this paper, the authors classify DfAM research studies in two categories: the first one focuses on DfAM methodologies that define comprehensive and systematic design frameworks oriented to the concept of combining functional requirements and manufacturing constraints in an AM-related design; the second one sticks to the scope of AM-enabled structure optimization design methods in terms of shape optimization, size optimization, and topology optimization.

4 Some Considerations About DfAM

In [9], the authors affirm that "manage design and represent design knowledge is affected by the no-tooling and sustainable manufacturing way", in other words, the new CAx systems, introduced by AM, enable designers to rethink the overall design process and revolutionize the traditional approach.

Starting from the classification proposed by Yang and Zhao [9], it is possible to reprocess the design methodology elaborated by Pahl and Beitz [10] on the basis of two completely different design approaches. The first one focuses on the greater freedom offered by AM technologies to designers for the creation of more complex geometries when compared to with traditional manufacturing processes (milling cutting, forming, casting process). The main difference resides in the fact that in traditional manufacturing processes shaping of materials takes place across the entire physical domain of the desired part whereas in AM processes the shaping of material primarily takes place in the formation of elementary elements (voxels, filaments, and layers) [11]. In this case, the impact of AM in the design process is reflected in the design considerations for aesthetic, manufacturing, assembly, and performance.

The second design approach focuses on the functional optimization. In this regards, the traditional design approach undergoes a substantial modification because the definition of the geometry is demanded primarily to the optimization tools and no longer to the designers.

4.1 Technological Optimization

The difficulty of defining, with simplicity and unambiguity, a DfAM approach related to the optimization of the technological process is mainly due to the large number of AM technologies currently available on the market, each of which requires to satisfy specific geometric and technological constraints.

Even if AM techniques allow high degrees of customization of the geometry with little impact on manufacturing constraints, complexity and cost [11], evidence dispelling the myth that everything is possible with AM.

In any case, whichever shall be the AM technology adopted, the designer will conceive the product in a new and different manner. In fact, there is no more an initial volume from which removes material, but a void to fill with creativity.

Ponche et al. [12] proposed a global approach aiming at defining part shapes subjected to the manufacturing process and functional requirements. In their research, functional specifications and AM process characteristics were directly combined at the early stage. This is because the choice of manufacturing direction and manufacturing trajectories, as well as manufacturing volume, microstructure, geometry, and manufacturing time, are the keys for a good DfAM [9].

In practice, in a design approach oriented to the AM, the designer has to learn to think about the product differently than he/she is used to with the traditional approach because he/she must take proper account of the 3D printing technology to adopt and its related technological and manufacturing constraints.

If compared to the traditional design method, a DfAM approach oriented to the optimization of the technological process entails two peculiarities:

1. it gives value to the designer's creativity and imagination. In fact, AM enables the building of highly complex shapes, multiple parts in one piece and functionally integrated objects. It allows also to improve product's performances by designing complex shapes for the inner geometries.
2. There is a change of position between technology and functional feasibility stages (Fig. 2). This is mainly due to the lack of knowledge of the designers on the potentials and limits of the 3D printing processes, and, at the same time, to the freedom left to them in conceiving the shape of the product.

These two aspects, strongly correlated with each other, entail the necessity for a continuous checking of the feasibility of the product by means of AM, with the consequence that the technical feasibility appears earlier in the design method.

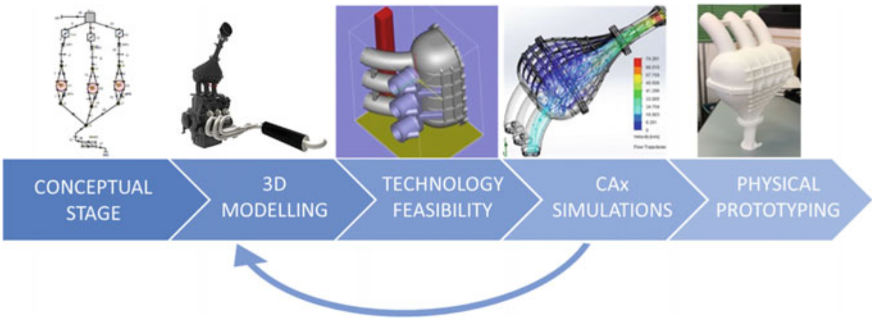

Fig. 2. Technological optimization approach

4.2 Functional Optimization

The optimization methods can be classified into two groups based on the predictability of the inner topology. If it is unpredictable, this type of optimization method is defined as a passive optimization; otherwise, it is called positive optimization [9]. Passive optimization methods include shape optimization, size optimization, and topology optimization. For a positively optimized part, its topology is usually in hierarchical patterns, such as lattice structure.

In literature, there is an extensive bibliography that proposes AM-enabled structure optimization design methods in which the functional optimization of the part is entirely focused on the function, carrying to the extreme the function-driven design approach. In fact, by adopting a functional optimization approach (Fig. 3), the optimization tools are the only responsible for defining the geometry that is determined on the basis of the functional requirements defined in the conceptual stage. Then, according to this approach, the form of the part is not the result of the designers' creativity, that requires simulation analysis in order to be approved for the production, but is the direct result of the functional optimization that may not require subsequent modifications because of the manufacturing capabilities provided by the AM technologies.

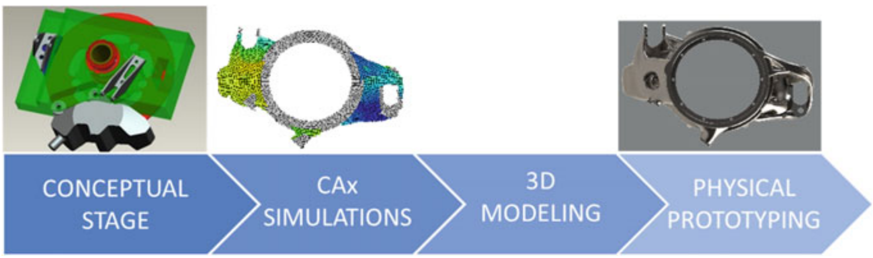

Fig. 3. Functional optimization approach

This is made possible thanks to two main reasons. First, 3D printing processes do not require binding manufacturing constraints. The second reason is related to an aesthetical evaluation of the geometries obtained as result of optimization analysis. In this regard, the literature presents many studies in which the geometries, outcomes of functional optimizations, are characterized by very particular shapes that could easily meet the aesthetic canons that leads to the definition of "beauty".

To sum up, according to a functional design approach, in the first conceptual stage designers define the functional requirements on the basis of which the functional surfaces of the product are established. These data are then elaborated by means of CAx tools that provide the optimal shape in terms of the goals and constraints imposed in the simulation. If on one side this approach would seem to exclude the contribution of the designer about the aesthetics of the product, on the other side it offers a new perspective on the development of new design forms.

4.2.1 Topology Optimization Analysis

Before the effective introduction and spread of the AM technologies in the industrial field, topology optimization analysis required an intensive and significant intervention of designers and engineers both for interpreting the analysis results and for managing the optimized geometry data used as input for the redesign of the product. To this end, some studies [13–15] have investigated these issues, due to the poor integration between topology optimization tools and CAD systems, by proposing methods and guidelines that facilitate the interpretation and extraction of useful geometrical information from the results of the topology optimization analysis, and support and simplify the geometric model redesign.

The necessity to redesign the optimized geometries, in order to obtain a feature based manufacturable product model, has been overcome thanks to the AM technologies. In fact, as above mentioned, AM offers the unique ability to fabricate incredibly complex geometries with organic shapes. Then the optimized geometries could be manufactured immediately without the necessity to import these geometries in the CAD system for further refinements. In this regard, the following Fig. 4 depicts some case studies in which topology optimization results have been fabricated by means AM technology as they are, without any intervention of the designers on the geometry of the parts.

It is worth to notice that in the examples depicted in Fig. 4, the designers have decided to print the results of the optimization analysis on purpose, in order to emphasize the "functional aesthetics" of the parts. In this way, the 3D modeling stage, usually adopted for the redesign of the optimized geometry, is then entirely skipped to switch directly on the prototyping stage.

Therefore, the re-design of the optimized model is at the discretion of the designer that may import the results of the optimization analysis into the CAD system in order to refine the geometry for an efficient fabrication via AM or simply to enhance its aesthetics. But, in any case, the geometry of the part is highly dependent on the function it has to fulfill.

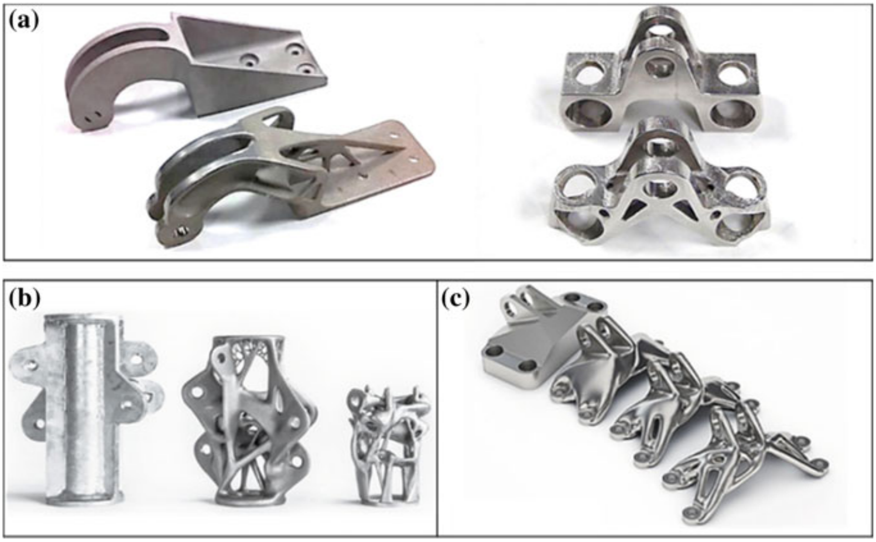

Fig. 4. Traditional design compared to optimized parts manufactured with to 3d printing technologies: **a** metal parts for aerospace field [16]; **b** element optimized with generative design [17]; **c** design topology optimization [18]

4.2.2 CFD Analysis

An interesting alternative to the function-driven approach based on topology optimization tools has been studied in a thesis work [19] carried out in collaboration between the University of Calabria and the Bochum University of Applied Sciences. The research focused on the functional optimization of a valve manifold block for hydraulic actuator (Fig. 5a) performed by means of CFD (Computational Fluid Dynamics) analysis. In particular, the CFD analysis has been carried out for calculating the optimal flow path with least pressure drop and highest average velocity (Fig. 5b). These results have been used as guidelines for the modeling of the geometry of the manifold, and for defining the loading conditions of the structural simulation processed on this geometry. Subsequently, the design has been refined for efficient production via AM in order to use the least material possible while avoiding building support structures in non-machinable features of the manifold (Fig. 5c).

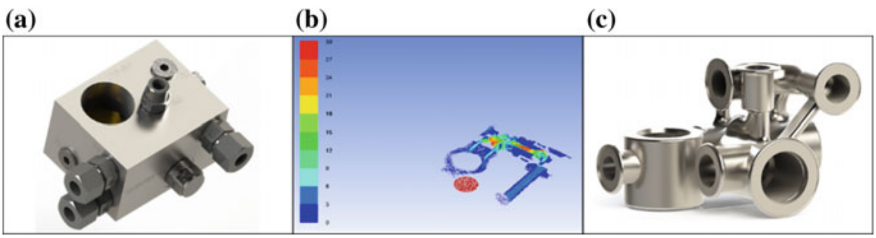

Fig. 5. **a** Initial design of the manifold block; **b** CFD analysis; **c** final design of the manifold block manufactured by means SLS technology [19]

Also, in this case, the tool adopted for the functional optimization, i.e. CFD analysis, defines the final geometry of the component that is then manufactured by means of AM technology without the need for designer interventions.

5 Conclusions

After many years of using consolidated methodologies and tools, the advent of AM has revolutionized the way of thinking about the product resulting in a reinvention of the design process. The paper has presented two different design approaches oriented to the AM fabrication of the product. The first approach focuses on the much greater freedom for the creation of complex geometries. The second one concerns with the optimization tools that allow designers to focus on the product's function thus relegating a detailed and accurate definition of the geometry in the last stages of the design process.

The two different design approaches discussed in the paper invites the reader to reflect on the tight relation that occurs between design methods and instruments and how it could evolve. If on one hand CAx instruments are traditionally conceived as tools that support and facilitate the practical implementation of design methods, on the other hand, we are assisting to the introduction and improvement of design tools, specifically developed to make more efficient AM technologies, that could influence and stimulate engineers to rethink and change the design process and then bring to the emergence of new design methods.

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