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Additive manufacturing adoption in product design: an overview from literature and industry

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Abstract

Additive Manufacturing (AM) technologies have greatly extended design possibilities and freedom. However, in the designer everyday work, the decision regarding the adoption of AM for some components is not straightforward. There is a need to evaluate the properties of the available materials, their compatibility with the specific application, redesign shapes accordingly to additive rather than subtractive or deforming processes, conceive merging components in unique complex multifunctional parts. Indeed, economic, procurement and logistics evaluations, possibly extended to the entire life cycle, are necessary to come to a decision for a new and radical solution. In this context, the paper investigates the complex set of information involved in the process to guide a designer in a structured assessment and evaluation of opportunities for the adoption of AM. The approach includes the analysis of the design requirements to evaluate the applicability of additive technologies. Selected design questions are presented as attention points to help designers in the decision-making process along with a metric to merge the answers in an overall compliance index. Finally, some test cases from the literature and industry are reported to validate the proposed decision process.

Keywords: Decision-making; Additive manufacturing; Design for Additive Manufacturing; Design process

1. Introduction

In the last years, AM technologies are representing feasible means to produce parts to be effectively employed in industrial products. AM is no more a laboratory technique to produce prototypes in a fast and low-cost way, but it is becoming an actual manufacturing option. Many industrial applications clearly show AM is able to overcome and substitute traditional processes such as machining or various forms of casting [1]. AM has the extraordinary potential of allowing very complex shapes. Even if the realization of a part is usually still expensive, it can be advantageous when the design of the components can benefit of highly optimized performances such as light weight, parts number reduction, first-class structural or thermo-fluid dynamic performances.

Established technologies such as sheet metal stamping, milling or casting are widespread in the industry and designers are usually aware of capabilities, obtainable shapes and parts behaviours and performances. Design rules come from experience and general design guidelines, generally referred as Design for Manufacturing and Assembly (DFMA) [2]. On the contrary, AM is characterized by a strong degree of novelty which is not limited to the specific manufacturing approach, i.e. composing the final shape layer by layer. AM introduces extended material characteristics, such as volumetric grading properties, possibility of more colours in the same part, availability of custom composite materials. Geometry can be finely controlled at different scales. It includes microscale (i.e. controlled porosity and texture), mesoscale (i.e. cellular structures instead of bulk material), and macroscale, giving the known freedom of designing organic and intricate shapes. Since material is added grain by grain, instead of being removed or globally formed, the design efforts are naturally concentrated on the minimization of volumes, sections and walls thicknesses, requiring careful structural evaluations. Additional issues include the necessity to think about the

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realization process, choosing the optimal part orientation, catering for supports, generating the shapes with adequate and novel CAD tools, applying necessary post treatments, and estimating realization times and costs.

Such aspects are only part of the wide range of knowledge a designer should consider applying AM in designing parts for the product to be realized. It is evident how difficult the design choices are, given the wide range of information to be managed. On the market several types of technologies, machines and realization options are available, and the relative evolution is very fast. Furthermore, from a design perspective, it is not just a matter of redesigning a part shape optimizing material consumption. The full leverage of AM possibilities is often reached with a rethinking of the existing solution, possibly starting from its functional structure [3].

In this context, this paper aims at the definition of a framework for systematically evaluate the data related to the design processes involved while adopting AM solutions. The goal is to establish procedures, based on such framework, to guide the designer in the identification of opportunities and to identify strategies to select materials, technologies, shapes and design tools to come to feasible solutions for a certain application field.

After a revision of the major technologies, design tools, constraints and opportunities provided by AM, the paper will present a systematic approach to support decision making for the development of new products and for the redesign of existing parts. The approach will be evaluated on a bunch of test cases from the literature and industry in order to validate its foundations.

2. State of the art

AM technologies have had a strong development during the last decades and this trend is expected to continue [1]. As a matter of fact, nowadays AM machines are no longer limited to the production of prototypes, rather they are implemented in the manufacturing sphere in order to develop complex final parts. Contrary to subtractive techniques, AM technologies produce the final products layer-by-layer, adding material where necessary [4].

AM processes consists in a digital dataflow that provides the instructions for the AM printer followed by a physical workflow that transforms the raw materials into final parts [1]. After an evaluation of the product requirements, the design workflow includes the creation of complex and organic shapes optionally using traditional CAD systems, new emerging tools or simulation-based systems [5].

At an early stage, there are many and heterogeneous aspects a designer must consider when deciding to adopt AM and before starting the workflow depicted above. Basically, the design requirements must be assessed against the possibilities and constraints given by the manufacturing technology [6]. In this context, the discipline of the DFMA has an important role. DFMA is the union of two methodologies, i.e. Design for Manufacture, which is the design for easing the manufacturing of the parts that will form a product, and Design for Assembly, which seeks to the improvement of the design of the product to facilitate the assembly phase [2]. In other words, the DFMA is founded on guidelines to help designers developing products in order to facilitate production and assembly, thus reducing production costs and times. For traditional production processes, standards and best practices have been developed from decades in order to avoid complications and inefficiencies during the production [7].

In the specific context given by additive technologies, Design for Additive Manufacturing (DFAM) is analogously defined as the design for manufacturability applied to AM. It includes design methods and tools whereby functional performance and/or other key product life-cycle considerations such as producibility, reliability and costs can be optimized subjected to the capabilities of AM technologies [8]. In this case, guidelines for approaching and designing with additive processes are under development [9] and standards related to the world of AM just refer to the basic principles of the technologies [10]. In the literature, few works aim to define guidelines to facilitate the work of designers who want to approach AM. In [11] the authors affirm that DFAM is just at the beginning and more studies are needed to get a more complete view. For example, there are no regulations to validate the final product and there are no complete and consolidated cost models to estimate manufacturing budgets at an early stage [12].

In the industrial practice the absence of clear DFAM patterns and guidelines often results in still occasional usage of AM at design stage. Also, there is only few software that allow to fully support the specific AM digital process. Some dedicated CAD tools are aimed at fostering the design of shapes to exploit the advantages of AM. Unfortunately, such functionalities are limited. In Table 1, the principal Topological Optimization (TO) and CAD software with specialized tools for AM are reported.

Table 1. TO and CAD software with AM modules, extended from [13]

Commercial software	Educational/Academic Software	CAD (specialized tool for AM)
Altair Optistruct	TopOpt	Autodesk Netfabb
Vanderplaats Genesis	META4ABQ	3D Experience
Simulia Tosca	CATOPTO	Nastran
Abaqus ATOM	BESO 3D	CREO 5.0
MSC Nastran	Pareto Works	Siemens NX
SolidThinking Inspire	Topostruct	
Within Enhance	ProTop	
OPTISHAPE-TS	ToPy	
PERMAS-TOPO	SmartDO	
FEMtools Opt	TITANS	

Most systems are traditional modelling kernels with expanded capabilities in lattice structures representation or leverage TO algorithms to generate optimized shapes [13, 14, 15]. Based on the load conditions and according to the designer needs, i.e. minimize mass or maximize stiffness, algorithms proceed removing the material from the initial design space where it is not necessary. Therefore, TO is not strictly usable with parts to be produced by AM, but it can cope also with traditional manufacturing processes [16]. Obviously, the designer must consider the manufacturing constraints given by the selected technology, including AM.

2.1. Overview of AM technologies

The evolution of AM over the past three decades has been extraordinary [1]. AM has experienced a strong growth from a promising set of technologies in the early 1980s to a market that was worth over $4 billion in 2014 and it is expected to reach USD 23.33 billion by 2026 [17]. AM techniques can be classified by the type of the process, by how the final construct is obtained and by the source of energy which is used for the phase change of the raw material, as summarized in Fig. 1.

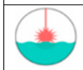
IMAGE	CATEGORIES	TECHNOLOGIES	CHARACTERISTICS
	Vat polymerization	Stereolithography (SLA) Direct Light Processing (DLP) Continuous Liquid Interface Production (CLIP)	High build speed Good part resolution High cost for supplies and materials
	Material extrusion	Fused Deposition Modeling (FDM) Fused Filament Fabrication (FFM) Atomic Diffusion AM (ADAM)	Inexpensive Multi-material Low surface finish and resolution
	Material jetting	Polyjet Multijet Printing (MJP)	Multi-material High surface finish Low strength material
	Binder jetting	Multijet fusion (MJF) Single-pass Jetting (SPJ)	Full-colour objects Require infiltration during the process Wide material selection High porosity
	Powder Bed Fusion (PBF)	Selective Laser Sintering (SLS) Selective Laser Melting (SLM) Direct Metal Laser Sintering (DMLS)	High accuracy Fully dense part High strength Powder recycling Support requirement
	Direct Energy Deposition (DED)	Laser Engineered Net Shape (LENS) Electron Beam AM (EBAM) Laser Metal Deposition with wire (LMD-w) Wire Arc AM (WAAM)	High deposition rate compared to PBF Repair of damaged part Functional graded part Require post processing
	Sheet lamination	Laminated Object Manufacturing (LOM) Ultrasonic AM (UAM)	High surface finish Low material, machine, processing cost Decubing issues

Fig. 1. AM technologies classification according to American Society for Testing and Materials (ASTM), adapted from [18].

Among the others, one of the most popular AM technique is the FDM, also known as material extrusion, because of its easiness to use and printers are much cheaper compared to other technologies. The FDM is often used to explore the possibilities offered by lattice structures thanks to low cost and versatility [19]. Although the material extrusion technique is widespread in the research field, its applications in the industrial and medical spheres are limited. Indeed, only polymeric material with limited mechanical properties can be employed and the surface finish is not optimal for many applications.

Nowadays, the most interesting options in the industrial field are the PBF and the DED process because it is possible to process metallic powders or wires, obtaining a high complex final object with high performance [11]. The most important difference between PBF and DED is that in the first process the material is melt after being deposited on the substrate, while in DED techniques the material is already melt as it is being deposited [20].

Recently, researches and attentions have also been posed on hybrid manufacturing [21], so as to overcome the severe limitation of the poor surface finish of the additive techniques. Hybrid manufacturing is defined as an alternation between an additive and subtractive process [22], in order to obtain a freeform object with high surface finish. In this context, in [23] the authors affirm that hybrid manufacturing presents significant opportunities to improve material utilization, part complexity and quality management in functional parts. However, one of the critical challenges is the determination of the optimal sequence of the two processes, which must be optimized to avoid tool collisions and to reduce the final total cost [24].

From an industrial point of view, some pioneer companies are using additive technologies for metal printing. For instance, aerospace companies such as Airbus [25] and Boeing [26] are pushing in this direction as they want to get lighter and lighter aircrafts to reduce fuel consumption. Airbus innovations teams have developed several components with direct metal laser sintering (DMLS) by EOS. For example, they have optimized a bracket reducing the total weight of the aircraft by 10 kilograms [27]. Boeing is also exploring the world of metal printing. In particular, in its 777x model there are numerous pieces printed in additives, such as small components, including temperature sensors and fuel mixers, and larger parts, like heat exchangers and separators [28].

As can be seen from this outlook, the world of AM technologies is constantly growing thanks to the expectations of spreading in many industrial sectors, such as automotive, aerospace and medical one [29]. However, the numerous limitations and the cost of the printed parts have greatly impaired their use. Moreover, there is a lack of knowledge on how to approach the AM technologies, making it unclear when it is possible, beneficial and convenient to use additive against traditional processes.

2.2. Opportunities and limitations in adopting AM

Like any other production system, AM presents advantages and disadvantages. The wide and mostly unexplored design space the AM is offering is very attractive for the industry, however, the complexity and novelty of reasoning patterns could result in significant factors to impede the implementation of AM techniques in the practice. Leaving the design teams evaluating possibilities in adopting AM technology on the basis of subjective and unstructured considerations may lead to skewed considerations and loss of opportunities.

According to Duty [30] it is possible to identify the main strength of AM in the simplicity to obtain freeform parts thanks to the layer-by-layer process without incurring in significant costs. Furthermore, it is possible to work at different level of length scale, i.e. leverage hierarchical complexity. For instance, complex lattice structures can be developed [31] to seek strength and lightness. Also, AM printers are able to build multi-materials pieces, thus customizing the performances according to the application needs. Moreover, AM technologies permits a strong reduction of the material waste because the material is added only where it is needed [32]. One of the primary advantages is the overall reduction of the weight of the final object compared to the traditional production methods thanks to the ease of producing complex and optimal shaped objects. Finally, other pros are related to the reduction of the logistic costs, i.e. manufacturing on demand, possibly locally, reducing also the lead time and the possibility to build already assembled objects.

On the other hand, the final work piece obtained with additive techniques normally requires further machining and surface treatments due to the poor surface finish, as well as unsatisfactory dimensional and geometric tolerances. Other important limits of the AM printers are the low build volume and the long process times, restricting their use for mass production. Also, when the design requires undercuts or overhanging parts, it is necessary to implement support structures which must then be removed. This post process is not always straightaway and requires attention in order not to damage the piece. To mitigate this problem, in the literature there are numerous studies aimed at creating self-supporting overhang structures, thus reducing the consumption of material and avoiding also supports removal [33]. Other limitations are related to the high energy consumption and, generally, lower mechanical properties compared to the pieces obtained with traditional technologies [30]. Finally, thermally induced tensions that are generated among the layers during printing must be carefully considered. High thermal tensions can lead to the mechanical failure of the part, sometimes even during the printing process itself.

Another aspect related to the design for AM is that it is often considered as a viable technology to produce complex parts resulting from TO. The opportunities of AM go further beyond the minimization of the material and cannot be relegated only to structural considerations. There is a need for a broader assessment that also includes functional aspects, as well as the possibility of adopting different and new design principles. For instance, biomedical products, such as prostheses and braces requiring lattice structures and superficial texturing [1], are examples of design processes not limited to pure shape optimization. In such cases, the designer must consider functional aspects and the beneficial features AM can provide to the final product [34].

From a structural point of view, it is worth mentioning that software for FEM analysis usually tents to adopt materials with isotropic behaviors, which is an invalid assumption for the parts obtained with AM techniques and the design and the simulation of lattice structures is generally complex. Moreover, there is not a comprehensive characterization of the numerous types of lattice structures that can be used to understand which cellular shape is most suitable for a certain application.

Finally, there are few inspection and control systems of the product realization phase, as well as there are no clear procedures that establish that the product is achievable with additive techniques. For example, Kumke et al. in [35], they have developed a modular framework on the base of VDI 2221 that could help designers during all the product development. However, their work does not address the issue of selecting candidates which could exploit the main benefits of AM. A study in this sense has been proposed by Lindemann et al. in [36], focusing on the selection of products that are compatible with AM. The authors have developed a Trade-Off Methodology (TOM) matrix that helps the designers to understand which products should be redesigned in order to exploit the advantages of AM. After collecting data regarding the part under consideration, the TOM matrix includes evaluations on the size of the component, followed by a complexity classification. Then, it considers the reduction of the assembly parts, the post processing, the material and the fulfillment of specific geometry conditions. Finally, the design optimization and processing time is considered too. The economic aspect is recommended only for more experienced designers. The authors have also developed a methodology to redesign an object suitable for the AM process. From their research it was concluded that the best method is to use TO software. The limitations of this study are connected to the narrow scope of application which exclude the development of new and original parts, while redesign processes are mainly linked to TO software only. Also, Klahn et al. in [37] address the selection of products suitable for the additive production. They have defined four criteria: integrated design, individualization, lightweight design and efficient design. These criteria are used to evaluate the suitability of products to be produced with additive technologies. A limit of this work is that these criteria are not exhaustive for an accurate and complete evaluation for the selection of candidates.

In conclusion, in the context of fostering the spread of AM applications, it is beneficial to develop approaches and guidelines to help the designer understand when and how to make the best use of AM technologies in order to improve designs with original and better performing solutions. Indeed, the discipline of DFAM is still at its infancy and additional studies are needed to fully understand the potential of AM in product design. Therefore, the main goal of this paper is to provide a method to support designers, even the less experienced, to better understand the potentiality offered by additive technologies in given design contexts. In particular, it aims at formulating guidelines to understand when it is potentially convenient to use AM. The core of the approach is represented by a set of evaluations, a collection of data regarding the product to be designed and a structured decision workflow to assess the design opportunities.

3. Approach

The development of a product for AM has been analysed in the context of standard design workflows [38, 39].

The first step of a design process is the collection of data on the product to be developed. The information in the scope of AM refers to the entire life cycle considering economic, functional, manufacturing aspects and includes: product type; geometric and mechanical specifications; quantity to be produced; material properties; required surface finishing; type of current production; current and expected cost of the product; current investments for the process; general economical, logistic and procurement aspects; type of contacts with other parts; need for part consolidation; main functions; principal design issues; load conditions.

After the task identification that refers to the company and market constraints, the designer and its team must think and select preliminary product ideas in order to formulate proposals, considering the benefits that additive techniques would bring to the product. They should clarify the tasks of the component, and produce a detailed requirement list, i.e. design specifications. Then, team aims to the development of a solution which is traditionally addressed in this order: a) identify essential problem; b) establish functional structure; c) search for working principal and working structures; d) combine and firm into concept variants; e) evaluate against economic criteria. Usually, these steps are fully addressed if a new product design is considered. In the case of redesign, a starting design solution is already provided.

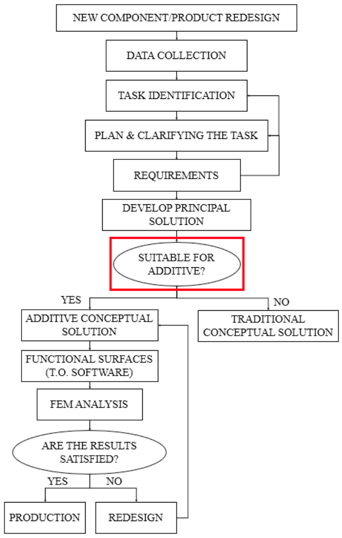


Fig. 2. Selection of suitable candidates for AM in the design workflow.

In order to support the process, reference questions are presented in Table 2, as attention points to help in the decision-making.

Table 2. Reference questions and given weight in the decision process.

QUESTIONS	WEIGHT
Q1) Is a problem of mass reduction?	9
Q2) Must production /logistical/ process cost be reduced?	8
Q3) Must material waste be reduced?	8
Q4) Is there a need to change material?	1
Q5) Is strong customization required?	7
Q6) Is lattice structure required?	7
Q7) Do I have to consolidate parts?	6
Q8) Do I have to integrate electrical circuits?	1
Q9) Do I have the necessity to complexify the shape?	9
Q10) Does the final product require areas with specific material (multi-material)?	5
Q11) Does the final product require areas with specific density (multi-density)?	5
Q12) Does the use of AM lead to a potential cost savings considering the entire life cycle?	10
Q13) Is the post processing phase limited?	9
Q14) Is the production batch size limited?	9
Q15) Is short delivery time required?	6

By asking these questions it is possible to focus on the product requirements and gather answers to assess if the component under consideration is suitable for AM. The list of the questions and the weights given to each of them has been formulated by a panel of students, researchers and experts of the field. Each panel member has expressed a value from 1 to 10 as a measure of the strength of the question as driver of AM opportunity. The value reported in the table comes from the average of the gathered values rounded to the closest integer.

One of the crucial points is the reduction of the product life cycle cost. The redesign or development of a new product with additive techniques is advantageous if it leads to money savings, which is rarely linked to a diminution of manufacturing cost itself, but a reduction of OPEX costs during use-phase in a life cycle perspective. For instance, a topologically optimized bracket developed for aeronautic applications, whether much expensive than the original support at manufacturing stage, can reduce the overall weight of the aircraft and leads to important savings in fuel consumption during the decades of plain operation. In section 4 test cases are presented to evaluate the effectiveness of the proposed approach.

A Compliance Index (CI) is introduced to measure the compatibility and suitability of AM for a product under consideration. It is defined as in the following Equation 1:

$$CI = 100 * \frac{\sum_{i=1}^{15} A_i * Q_i}{\sum_{i=1}^{15} Q_i} \tag{1}$$

In order to calculate the index, a value Ai from 1 to 5 is to be given to each question in order to assign levels of importance for each case studies. Then a score is computed as the weighted average of the collected values, where Qi represent the weights reported in Tab. 2. Finally, values are normalized dividing the result by 5 and multiplying by 100 to obtain the index in the form of a percentage.

The CI gives a relative measure of the possibility to keep on with the process and search for a new solution based on AM. The threshold for the index depends on many factors and it is not possible to fix a standard value. The samples collected in the next section suggest a value at least around 60%, but of course it depends on the type of products, requirements, application field and company strategy. In case the designer concludes that the final product would potentially benefit from AM, then he can move on to the next phase, otherwise he will try to further optimize the existing solution in the context of traditional manufacturing technologies.

Two main redesign methods of the principal solution have been identified to take full advantage of AM. The first method is using TO software and seeking for maximum reduction in material consumption. An alternative method of redesign is to start from functional surfaces and proceed with required geometrical features. In the literature, functional surfaces are targeted in two opposite ways [40]. A first alternative moves from the maximum available design space and then it removes material preserving the functional features and reducing the overall mass. This method is called top-down strategy as it starts with a bulk shape, breaking it down. The second approach is a bottom up strategy as it begins with the interfaces, defining the maximum envelope constraint, and then adding functional features and structural reinforcements. The second procedure moves from small and disconnected volumes and proceeds building up the required structure from them. It has been noticed that bottom up approach can obtain design that have lower mass compared to its top down counterpart, but it requires geometric modelling capabilities that are not yet common in commercial CAD packages or, in any case, it requires good experience in the modelling field [1].

The final step of the process is a careful validation through FEM software, selecting a material for the part compatible with the ones that can be used in additive processes. This step is critical in AM techniques. Given the nature itself of the process, i.e. adding material, the designer will shape the part recurring to limited use of material and small thicknesses. On the contrary, in subtractive processes the production costs could even rise if the part is too carved, generally resulting in oversized geometries which do not usually need to be carefully verified.

If the designer is able to find a result which satisfy the constrains, an interaction with the AM technology expert can start in order to optimize the design. In this step, having defined the basic characteristics of the part, i.e. overall dimensions, material, surface finishing and tolerances, the technologist can choose the process and the printer that best suit the needs. An important aspect that designer and machine expert must consider are the thermal stresses generated during printing. Machine parameters as well as geometry changes should be carefully considered to minimize manufacturing stresses and guarantee a waste free realization.

While defining the realization process, the designer and the technologist must choose necessary post processing activities, i.e. heat treatments, machining, etc., to achieve the required mechanical properties and surface finishing. Suitable cost models are employed in this phase to select machines that guarantees lower production cost, which often corresponds to a shorter production time. Such evaluations can be supported by software systems such as Autodesk Netfabb Ultimate [15] which provides libraries of printers to be chosen and allowing the calculation of the production time from the part geometry. Finally, the designer releases the final CAD file in STL, 3MF or STEP formats to realize a first prototype to be physically evaluated and tested.

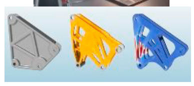
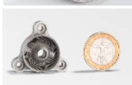
Specifying, the development of a new product involves the collaboration of several professional figures with different backgrounds. Generally, high level of experience is required from all the fields of expertise. Brainstorming and meetings are beneficial, as well as good communication between the various actors, since AM offer broad design spaces and revolutionary solutions can be identified.

4. Applications

This section presents some interesting case studies found in literature to validate the proposed evaluation approach. The examples have been selected from the literature, industrial and medical sector. They have been reported as they cover relevant applications of AM. Generally speaking, parts which leverage AM can be divided into 5 categories, namely: i) structural components whose goal is to maximize stiffness while removing as much material as possible, ii) products that need a complex and specific shape aimed at increasing fluid dynamic efficiency, increasing thrust or obtaining conformal cooling, iii) rapid tooling using additive techniques to produce tools for other parts, for instance moulds, and iv) all those parts where high customization is required, such as biomedical or fashion products. Finally, other examples include v) prototypes, which are used, for example, to make an evaluation of dimensions and then obtain the final product with other techniques.

In Table 3, examples from the literature are presented both covering cases of redesign and development of new products.

Table 3. Selected examples form the industrial and scientific literature.

Test case	Aim	Image
a) Metal bracket *Airbus [25] - 2014*	Mass reduction	
b) Fuel system part *Airbus [25] - 2014*	Part consolidation	
c) Folding wings *Boeing [26] - 2018*	Increase aerodynamic efficiency	
d) Bell crank *Altair [14] - 2016*	Mass reduction	
e) Bracket *Altair [14] - 2018*	Mass reduction	
f) Aeronautical turbine *Prima Additive [41]*	Shape complexity	
g) Combustion chamber *Prima Additive [41]*	Part consolidation / fluid dynamic efficiency	
h) Small rotor *Prima Additive [41]*	Shape complexity / Part consolidation	
i) Bracket *Prima Additive [41]*	Mass reduction	
j) Tower *Prima Additive [41]*	Shape complexity	
k) Turbine blade *Prima Additive [41]*	Shape complexity	
l) Engine piston *UNIMORE [42] - 2017*	Mass reduction	
m) Hip prosthesis *[43]*	Custom shape	

The first example is a bracket developed by Airbus [25] (a). Here the redesign goal has been focused on the reduction of the material to save weight. In this context, the customer airline experiences a reduced weight of the plane by 10kg, limiting fuel consumption during the flight. Another application of the same company concerns the redesign process of a fluid injection system. In this case, the number of parts has been decreased, lowering production and assembly costs (b).

The third test case regards folding wings developed by Boeing [26] (c). The company has adopted this technique to increase efficiency during flight with reduction of fuel consumption, while restricting the size of the plane when it is in the airport. Other cases come from *Altair* [14], a software house who has specialized in the field of TO. With its two software systems, *Optistruct* and *Inspire*, it is possible to conceive original shapes of components starting from loads, constraints, and design objectives. The reported cases are the bell crank (d) and a bracket (e). In the first case, a topological optimization was addressed, as it was intended to reduce the mass of the system, while, in the second example, a lattice structure has been implemented and optimized. It is evident as the obtained structures are very complex and difficult to be produced by traditional techniques, therefore the use of AM printers is a convincing choice.

Prima Additive [41] is a major Italian business reality and it is a division of *Prima Industrie Group*. It is a leading specialist in AM processes, systems, and solutions worldwide. Prima Additive offers a range of metallic laser technologies, namely Powder Bed Fusion and Laser Metal Deposition. The examples reported from this company (f to k) require the use of additive techniques as they have features that are difficult or even impossible to obtain with traditional processes, due to concave surfaces, all-in-one assembly and presence of lattice structures.

Then, an engine piston [42] (l) that was optimized through a TO software is presented. The authors have initially defined the design space where the software has removed material according to the objective function and constrains, i.e. minimize the mass within a target stiffness. Three different load cases have been considered: top dead centre during combustion, top dead centre at the beginning of the induction stroke and instant of maximum piston thrust force. Each load case was analysed independently to better understand how the density distribution is influenced by the load path and by the design constraints.

Finally, a prosthesis (m) has been considered as a typical example in the medical field [43].

Qi/ Cases	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	CI
a	5	5	5	1	1	2	2	-	5	2	2	5	1	3	3	66.3
b	5	5	5	1	1	1	5	-	5	3	3	5	2	4	2	72.9
c	2	5	3	1	1	2	2	-	4	4	4	5	1	5	2	62.2
d	5	4	5	1	1	1	1	-	2	1	1	1	1	1	3	42.8
e	5	5	5	1	1	3	2	-	5	1	3	5	1	3	3	67.7
f	1	4	4	1	1	1	1	-	5	1	2	4	2	4	3	53.7
g	4	5	5	1	1	1	5	-	5	3	3	5	1	3	3	68.7
h	5	5	5	1	1	1	5	-	5	2	2	5	1	2	4	67.9
i	5	5	5	1	1	3	2	-	5	1	1	5	1	3	2	64.4
j	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
k	3	3	4	1	1	1	1	-	5	1	1	5	3	3	1	54.3
l	5	5	5	1	1	1	3	1	4	2	3	4	1	3	3	63.2
m	3	5	5	1	5	5	4	-	5	2	3	5	2	5	3	81.4

Fig. 3. Scores given to the selected cases and resulting compliance indexes.

In Fig. 3 the values of the answers and the compliance indexes are reported for the selected test cases to objectivate the previous statements. These values were given by the panel of students, researchers and experts of the sector introduced previously. It must be noticed that question *Q8* is closely linked to the integration in the mechanical design of electrical applications. Unfortunately, this question does not contribute to the calculation of the CI for any of the selected test cases. However, in the case of dealing with a product that also includes electrical circuits, the question *Q8* will have a significant weight. The parts with a greater CI and therefore those more suitable for AM, are the hip prosthesis (l) and the fuel system (b). On the contrary, by applying the proposed metrics, the example that benefits to a lesser extent of AM techniques is the crank presented by Altair (d) as the shape is not extremely complex and obtainable through traditional techniques. Attention is posed by the obtained CI to the turbine (f) and the turbines blade (k) presented by Prima Additive and the folding wings (c) developed by Boeing. In-depth studies will have to be done in order to understand which production method is most suitable for these products. In this context, the two examples designed by Prima Additive present complex shapes which could be difficult to obtain with traditional techniques. Regarding the towers (j), the authors have not been taken into consideration as it does not fit direct industrial applications, but it is only a demonstrative geometry.

According the approach presented in section 3, the main cases where the potential of AM printers can be fully exploited are related to the reduction of the mass, as it is possible to obtain light products with complex shapes that are difficult to obtain with traditional techniques. Other examples concern the design of components with a strong demand for customization, such as biomedical and/or dental products. In these cases, complex shapes are obtained which additionally require lattice structures, that are impossible to achieve with traditional techniques.

5. Conclusions and future work

There are few works in the literature that address the evaluation of AM adoption in early product design. The main objective of this paper is to review guidelines for designers approaching AM, in order to support the initial decision making and the design process. To this aim, an approach is presented to cope with both the redesign of existing parts and the definition of new products. Following a set of questions, the designer can assess if the product is suitable for the AM production.

Finally, a series of case studies in literature have been presented and analysed to validate the proposed evaluation method. Adding up, it is possible to conclude that there are key design drivers, namely high customization level, complex shape, and necessity for lattice structures, that make the choice for AM suitable or almost mandatory. However, intermediate situations emerge, whose opportunity for AM can be assessed properly by the method.

As future works, multiple extensions are possible. First, the authors are further developing the approach including more evaluation aspects, thus enforcing the concept of DFAM. In addition, additional case studies will be developed to create detailed guidelines for the design phase. For instance, cost models that includes the life cycle costs related to the AM are necessary for a correct evaluation of the applicability of the technology. This model needs to analytically consider the various components of the cost, and the phases of the entire life cycle encompassing production, use and dismantling.

Finally, the quantity of assessments which are needed to be evaluated, as well as the numerous types of technology, machines and process options, requires the definition and implementation of proper IT tools in order to support and facilitate designers in the evaluation of opportunities in a faster and more precise manner.

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