sustainability

Review

Design for Additive Manufacturing: A Systematic Review

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Abstract: The last few decades have seen rapid growth in additive manufacturing (AM) technologies. AM has implemented a novel method of production in design, manufacture, and delivery to end-users. Accordingly, AM technologies have given great flexibility in design for building complex components, highly customized products, effective waste minimization, high material variety, and sustainable products. This review paper addresses the evolution of engineering design to take advantage of the opportunities provided by AM and its applications. It discusses issues related to the design of cellular and support structures, build orientation, part consolidation and assembly, materials, part complexity, and product sustainability.

Keywords: additive manufacturing (AM); design for additive manufacturing (DfAM); opportunities; applications; design guidelines

1. Introduction

Additive manufacturing (AM) is the process of adding material to produce physical objects from a digital data model [1]. Unlike traditional manufacturing processes, where the material is removed to generate a part, most AM techniques depend on the additive process that gradually builds a component layer after the other [2]. AM techniques are used to create prototypes, models (rapid prototyping), parts of end-use (rapid manufacturing), and tools for long-term mass production of parts (rapid tools) [2,3]. Operations can be classified into four main categories according to the operation principle [4]: addition, subtraction, hybrid, and forming operations. According to the American Society for Testing Materials, AM technologies can be divided into seven categories as follows: direct energy deposition, binder jetting, powder bed fusion, material extrusion, sheet lamination, material jetting, and vat polymerization [1].

The growth of AM has been nothing less than remarkable in the last three decades. Since the late 1980s, AM has been investigated and developed commercially. This growth has been made possible by advances in AM materials and technologies and driven by market factors requiring its use, such as shorter product development cycles, increased demand for personalized and tailored goods, increasing focus on sustainability regulations, reduced production costs on lead times, and the emergence of new business models [5]. Over the last decades, the research community has developed and implemented new AM techniques and applied them in the biomedical [6,7], aerospace [8], and automotive [9]. These AM techniques include Stereolithography (SLA) [10], Selective Laser Sintering (SLS) [11], Fused Deposition Modeling (FDM) [12], Three-Dimensional Printing (3DP) [13], Laminated Objective Manufacturing (LOM) [14], and Laser Metal Deposition (LMD) [15]. Due to the increased precision of AM machines, a wide range of materials, and mechanical properties similar to other manufacturing techniques, have reached a level of maturity. Hence, AM holds the potential to become a new standard for product manufacturing. It aims to integrate the advantages of engineering design and prototypes into a final functional product [16].

The unique capabilities of AM include the complexity of the shape, material, and functionality, hierarchical complexity, mass customization, product personalization, and product decentralization [17,18]. In using these exceptional characteristics, the challenge for designers is to create high-quality parts that meet design requirements, such as functionality, mechanical properties, and cost, while ensuring the manufacturing capability in AM systems.

The advantage of engineering and material for AM freedom of end-use parts creates a world of opportunities. However, not all parts can be created or are cost-effective for production using AM because of the manufacturability constraints of AM processes, such as printing thin poles and hanging features [19], small features such as small holes, thin walls, and slots [20], overhang structures [21,22], and enclosed voids that prevent removing the unmelted material/support structure [23]. Besides, thermal distortion [24], anisotropic material properties [25], and cost and time [26] are the inherent limitations of AM processes. It should be noted that the AM manufacturing constraints differ between different types of AM process. Realizing the capabilities and limits of AM can help designers generate parts suitable for AM manufacturing [3].

The Design for Additive Manufacturing (DfAM) objectives and goals consist of three levels of abstractions of traditional design for manufacturing and assembly (DfMA) [3]: (1) provide tools, techniques, and guidelines for adapting the design with a certain set of final manufacturing constraints; (2) measure and understand the impact of the design process on the manufacturing system to improve the product quality; and (3) determine the relationship between design and manufacturing and its impact on designers and practices. However, although the definition of DfMA and its goals may be applicable to AM techniques, the knowledge of design, tools, rules, processes, and methodologies will vary significantly for DfAM [3]. The major technical challenges preventing the overall penetration for AM in the industry are the development of such knowledge, tools, rules, processes, and methodologies for AM [27].

This paper aims to review DfAM in terms of trends, considerations, opportunities, techniques, and applications. The development of DfAM techniques and methodologies is considered one of the best key challenges of basic AM principles. The insufficient understanding and implementation of DfAM restrict AM's overall market penetration, thereby preventing the maximum usage of AM by designers and preventing AM from achieving its full potential. A new systematic collection of DfAM approaches is proposed in this review based on the following classifications: cellular structures, consolidation and assembly of parts, materials, support structures, build orientation, part complexity, and product sustainability.

2. The Classification of Design for Additive Manufacturing (DfAM)

2.1. Cellular Structures

Cellular structures [28] are porous structures that have gained significant attention from engineers and researchers because of their ability to distribute materials in ideal locations to enhance the mechanical performance [29] in various aspects, such as high strength-to-weight ratios, high heat transfer capacity, thermal insulation, and energy absorption. Cellular structures consist of an interconnected network of solid supports, plates, or small unit cells (periodic or random) and are common in nature, such as in the skeleton of living cells [30], sponge, bone [31], cork structure, coral [28], wood [32], butterfly wings [33], fungi mushrooms, and many other growing organisms [34]. Note that the cell topology, shape, and size greatly influence the mechanical properties of cellular structures [35]. A previous report [36–38] stated that cellular structures can be classified into four main types, which are foam [39] (Figure 1a), honeycomb [40] (Figure 1b), lattice [41] (Figure 1c), and other constructions [42] (Figure 1d).

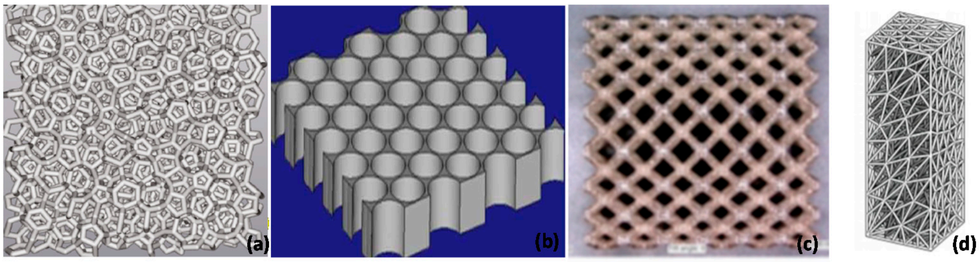

Figure 1. Cellular structure classification: (**a**) foam (Figure reused with permission from [39]), (**b**) honeycomb (Figure reused with permission from [40]), (**c**) lattice [41], and (**d**) other constructions (Figure reused with permission from [42]).

Several studies have designed different types of cellular structures with unique characteristics. The simplest cellular structures are the two-dimensional honeycomb [43] and three-dimensional (3D) foams [28]. A structure with only solid edges is called an open-cell structure, while that with solid edges and faces is called a closed-cell structure [28]. Foams and lattices [44] are cellular structure categories based on the uniformity of unit cell connectivity [45,46]. However, common AM cellular structures are under the lattice category. The primary elementary designs are in addition to a periodical octet-truss lattice design such as octagon truss (Figure 2a), cubic truss (Figure 2b), open-cell lattice (Figure 2c), and periodical lattice structure (Figure 2d) [47]. Lattice structures have been historically produced using manufacturing methods, such as casting [48], metal wire assembly [49], and snap-fitting [50]. Nevertheless, these processes are complicated and costly and have to comply with many design restrictions, despite the lightweight advantages of lattice structures. Thus, despite their advantages, they have not been commonly utilized [51]. Today, more complex lattice structures can be efficiently produced because of the advances in AM [5,52].

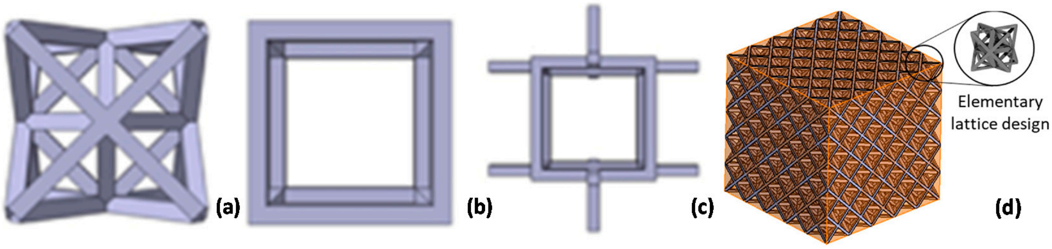

Figure 2. Lattice design examples: (**a**) octagon truss, (**b**) cubic truss, (**c**) open-cell lattice, and (**d**) periodical lattice structure [47].

A significant and growing collection of literature on the DfAM and optimization methodologies for cellular structure has been widely used in a large number of published studies [3,37,53–60]. The optimization and modeling of the cellular structure have gained great popularity in recent years as a promising approach to material and structural design [36,53,61–67]. Moreover, optimization and modeling are used to design cell structures to achieve various optimization objectives, such as maximum bulk coefficients [68], maximum thermal expansion [69,70], negative Poisson's ratio [71], and multifunctional properties [72]. Moreover, cell structures can be created by choosing the geometry, shape, and size of the cell unit and building the size based on the cell unit [73–75]. The size, orientation, boundary conditions, and type usually affect (but not always) mechanical properties, porosity, and deformation of the resulting materials [76,77]. AM has been utilized to produce stiff and extremely light structures [78], auxetic structures [79–81], and unit cell molds for auxetic structures [82].

It can also be used to produce auxetic structures [83] and unit cells for acoustic materials with a negative refractive index [84].

The cellular structure has the following main advantage: the material is placed only when a specific application is needed. The design and manufacture of cellular structures strive through the desire to provide expensive functional materials, high performance, energy consumption, construction time, high hardness/weight ratio [28,37,56,85,86], excellent energy absorption features [87–89], low thermal conductivity [90], great acoustic and thermal insulation properties of aerospace structures [91], medical, automotive parts, and engineering products [37,92]. The cellular structure has been applied in various new areas, particularly in the aerospace, biomedical, and automotive industries. Aerospace components must be strong and lightweight; hence, they are usually made of super-alloys and high-temperature ceramics, which are very expensive. Considering its high strength-to-weight ratio, the cellular structure is used in the aerospace industry to enhance the weight-to-performance ratio that can increase aircraft efficiency. Many reported studies [93–100] used lattice structures to reduce the weight of components similar to aerospace parts. Foam aluminum gives higher crippling resistance [101] and isotropy mechanical properties; therefore, aluminum and titanium foaming sandwiches are used for the tail booms of Boeing helicopters. Moreover, the cellular structure is exploited in the biomedical/healthcare sector because of the high strength of weight and the maximization of surface area characteristics [56,102–109]. According to biocompatibility, titanium and cobalt-chromium alloys are the most common materials used in dental and prosthetic implants. The most useful applications are Osseo-integration and improved installation of biomedical implants compared to porous coatings. Cellular structures are also used in bone and tissue engineering structures [105,106,108,110], biological instruments [111,112], biomedical implants [101], aerospace [42,113,114], flat configurations (e.g., sandwich) [115], medical [116], real engineering applications [47], and vibration isolation [117].

2.2. Part Consolidation and Assembly

Part consolidation (PC) is an important design strategy for reducing the number of parts and simplifying the product structure [118]. Using this technique aims to reduce costs and weight and enhance performance. PC enabled for AM, considering their freedom to distribute and configure materials, launched the possibility of reducing the number of parts [119–121]. Industries [122] and academics [123,124] have demonstrated a passion for applying emerging new capabilities in product innovation. In particular, General Electric (GE) presented a consolidation of 900 parts of a helicopter engine, including fasteners, into 14 parts. The consolidated design is approximately 40% lighter and 60% cheaper [125]. The well-known and first case for PC reported using AM capabilities is the aircraft duct redesign [126]. A total of 16 parts of aircraft were needed to complete this duct considering the limitations of the conventional manufacturing process. After the process consolidation part, only one part needs to be manufactured by the AM process. AM has capabilities in part consolidation and assembly such as: throttle pedal [127]: before consolidation (Figure 3a), and after consolidation (Figure 3b). Additionally, the design for assembly (DfA) in AM also contributes to a reduction in the complexity of product structures to obtain an optimum assembly-based design with minimal processing time, including assembly and buildup time. Optimal assemblies and their corresponding orientations are derived to reduce the overall processing time [128].

DfAM was introduced in this research to take full advantage of the freedom of design in terms of PC and redesign [17]. Most of the previously reported studies in DfAM aimed to improve product performance while reducing costs [3,129,130], improving functionality [131], and focusing on design guidelines for successfully printing parts under AM limitations [132]. Punch et al. [59] introduced a new DfAM methodology to design requirements and consider manufacturing and assembly specifications. This methodology contains three processes, namely functional optimization, and part orientation, to meet the design requirements. Meanwhile, Rosen [133] utilized a computer-aided DfAM system based on a structure-property–behavior framework for process planning, supporting the part modeling, and manufacturing optimization to find optimal processing and assembly time. Thompson et al. [3] proposed design opportunities, advantages, and freedoms at the AM part level. They described PC as a process of consolidating parts for assembly into one printable object [134]. Combining parts is considered to reduce the number of parts.

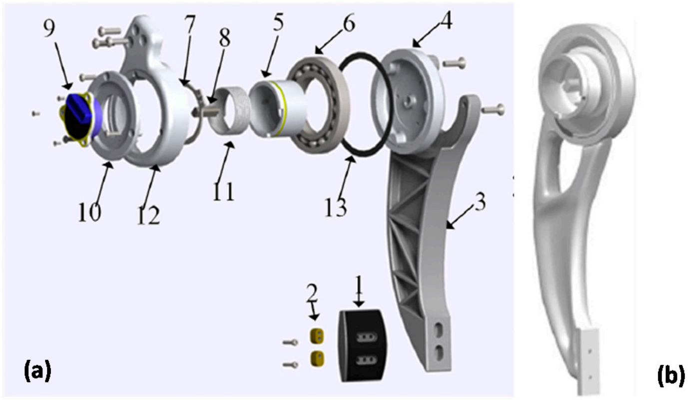

Figure 3. Throttle pedal (Figure reused with permission from [127]): (**a**) before consolidation, and (**b**) after consolidation.

The DFA contributes to the reduction in the complexity of product structures [118]. Reducing the number of parts is also recommended as a general guideline [118]. One of the main benefits of AM is enabling designers to combine assembly parts into a single object, regardless of the shape complexity [135,136], and opening the door to reduce assembly operations. As regards the advantages of the design PC and assembly through AM, the PC design methodology has received attention from designers in terms of production redesign for enhancing performance. Parts designed by conventional manufacturing have some limitations compared to AM capabilities [137]. The main benefits of PC are as follows: the complexity of production management and part assembly is reduced; tedious assembly operations that improve the production efficiency are avoided; and assembly tools (e.g., fixtures and fasteners) are no longer needed, which reduces the production costs [138].

2.3. Materials

Various materials are used for AM, and research on further developing these materials is in progress. Today, different categories of materials are used (e.g., metals, alloys, ceramics, plastics). Accordingly, previous studies on materials used for AM [139] classified materials into five main types (Figure 4). AM technologies can process a wide range of materials. Metal AM offers excellent growth opportunities. The 3D printing metal and alloy processes usually involve melting metallic feedstock (wire or powder) using an energy source, such as an electron beam or a laser. Various metals and alloys (e.g., stainless steel and tools [140–143], some aluminum alloys [144,145], titanium alloys [146–149], and nickel-based alloys [150,151]) can be made using AM processes. Polymers and composites are among the most popular materials in the 3D printing industry because of their versatility and ease of use in various 3D printing processes. Different polymers and composites, such as photopolymer resins [152,153] thermoplastic polymers [154–156], and alumina powders [157–159], are used in AM. AM has also become an essential technique for producing advanced materials, including ceramics. Examples include polymer-derived ceramics for instance, UV-curable preceramic monomers are mixed with photo initiator (Figure 5a), the resin is exposed to UV light in an SLA 3D printer or through a patterned mask (Figure 5b), a preceramic polymer part is obtained (Figure 5c), and Pyrolysis converts the polymer into a ceramic (Figure 5d) [160], that can remove an organic binder and does not require post-processing in contrast to using ceramic filters, which consequently shortens the production time with a very smooth surface, such as 3D-printed concrete (Figure 6) [161].

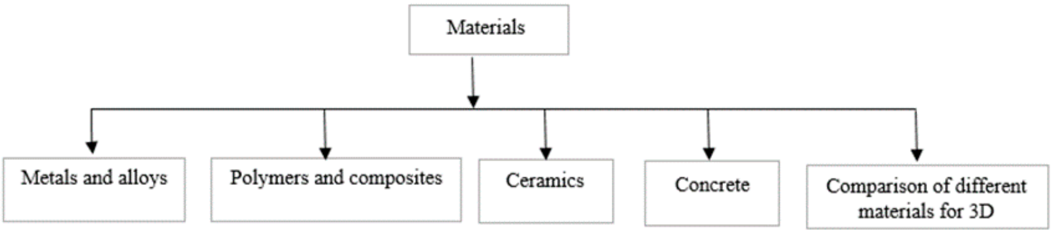

Figure 4. Classification of materials used for additive manufacturing (AM).

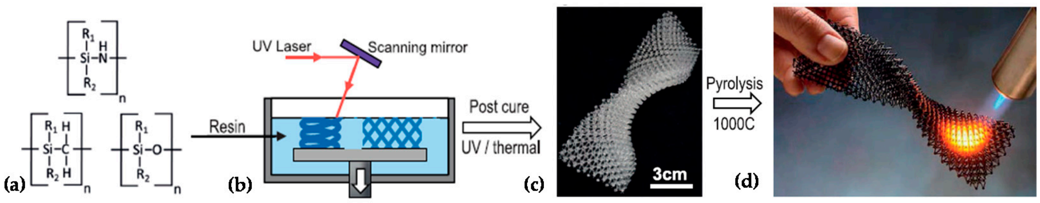

Figure 5. 3D-printed polymer-derived ceramics: (**a**) UV-curable preceramic monomers are mixed with photo initiator, (**b**) the resin is exposed to UV light in a Stereolithography (SLA) 3D printer or through a patterned mask, (**c**) a preceramic polymer part is obtained, and (**d**) Pyrolysis converts the polymer into a ceramic (Figure reused with permission from [160]).

Figure 6. 3D-printed concrete (Figure reused with permission from [161]).

Other examples are concrete, such as that with a 3D-printed concrete structure [162–164], and other 3D materials [165,166].

The different materials can be used in AM because of various benefits, including multifunctional optimization, reduced material waste, mass customization, the possibility of repairing damaged or worn metal parts, fast prototyping, control of lattice porosity, the printing of complex structures and scaffolding for the human body, and the usage of no framework [139]. The materials manufactured by AM have been applied in various new areas, such as polymers (e.g., rapid prototyping of toys and advanced composite parts) [167], metals, ceramic and polymers (e.g., biomedical, automotive, electronics, cladding, and aerospace (Figure 7a–c), lightweight and smart structures, and heat exchangers) [17,167], ceramic, concrete, and soil (e.g., large biomedical structures and buildings) [168].

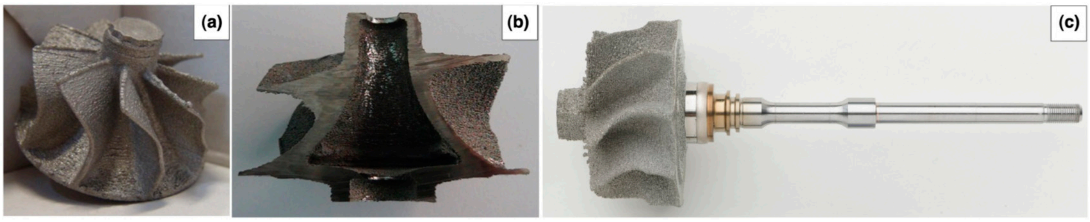

Figure 7. Aerospace and automotive applications using several materials (Figure reused with permission from [169]): (**a**) TiAl turbocharger wheel produced by electron beam melting (EBM), (**b**) cross section of a hollow TiAl turbocharger wheel, and (**c**) joining trial.

2.4. Support Structures

Throughout the printing process, additively produced parts go through several states, in which different forces are raised (e.g., gravitational forces in case of overhang features, thermal and residual forces, and forces generated by the AM process itself), in which support structures are becoming crucial. Different strategies like orientating the part during the building process, designing the part such that it does not need to be supported during building (self-supporting), and including support structures are usually adopted to reduce/eliminate the effects of these forces on the part accuracy, strength, and functionality.

Support strategies depend on AM processes and/or materials. In polymer SLS parts, the powder bed acts as a self-supporting bed, and support structures are not necessary. However, metallic SLS parts need support and cannot be eliminated. Buoyancy force and shrinkage induce distortion during the photo-polymerization processes. Moreover, support structures are required for better quality and accuracy. For material extrusion processes, both thermal residual stresses and gravity necessitate the need for support structures. For powder bed fusion processes, the support structure mainly aims to counter the thermal residual stresses generated during the melting–solidification processes. For metal powder bed fusion processes, especially laser-based systems, the large temperature gradients generated during the fabrication process often require carefully designed extensive support structures. Note that support structures in AM metallic processes are often required, even if the part is mechanically self-supporting, because supports act as a pathway for heat conduction that reduces heat-related failures and thermal residual stresses. In these cases, the support must be designed to fulfill both mechanical and thermal requirements [3].

Due to the AM processes' inherent characteristic of the layer-by-layer building, overhang features cannot be accurately built without adding support structures. In these cases, support structures are designed such that designers should consider the building time, removability, manner of removal, and quality of the part after support structure removal. In general, the part cannot be printed accurately if the inclination is below 45° with respect to the baseplate. Above this angle (i.e., overhang angle: larger than 45°), the support is called self-supporting [65]. Thus, the overhang angle is a constraint in DfAM. Rezayat et al. [53] defined the overhang condition as an element definition, meaning that an element is not overhanging at 45° if any of the three adjacent elements below one element is filled with material. Wadea et al. [170] studied the deformation of overhang parts with different inclination angles (Figure 8). Many studies have been performed to support structure removability [171,172], reduce the support volume [173–175], and eliminate the support [176,177] and self-supporting structure [65].

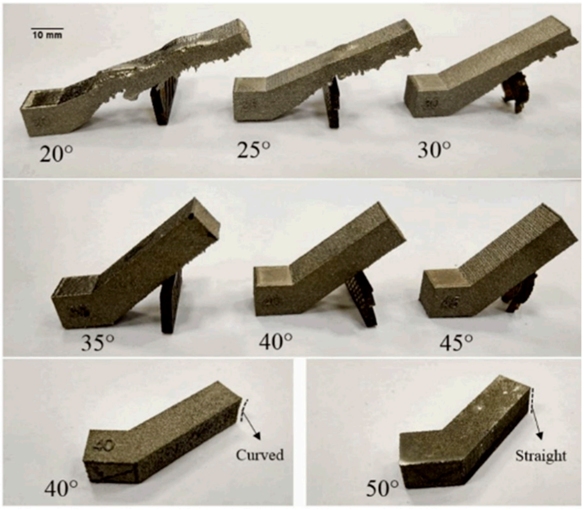

Figure 8. Deformation with different inclination angles (Figure reused with permission from [170]).

The support structure volume, building time, and manufacturing cost are typically functions of the build orientation. For simple parts, the build orientation is usually identified directly by designer experience. However, complex parts need to optimize the building orientation, as reported in [173,178,179]. Figure 9 [179] illustrates examples of different build orientations and their effects on building time and quality.

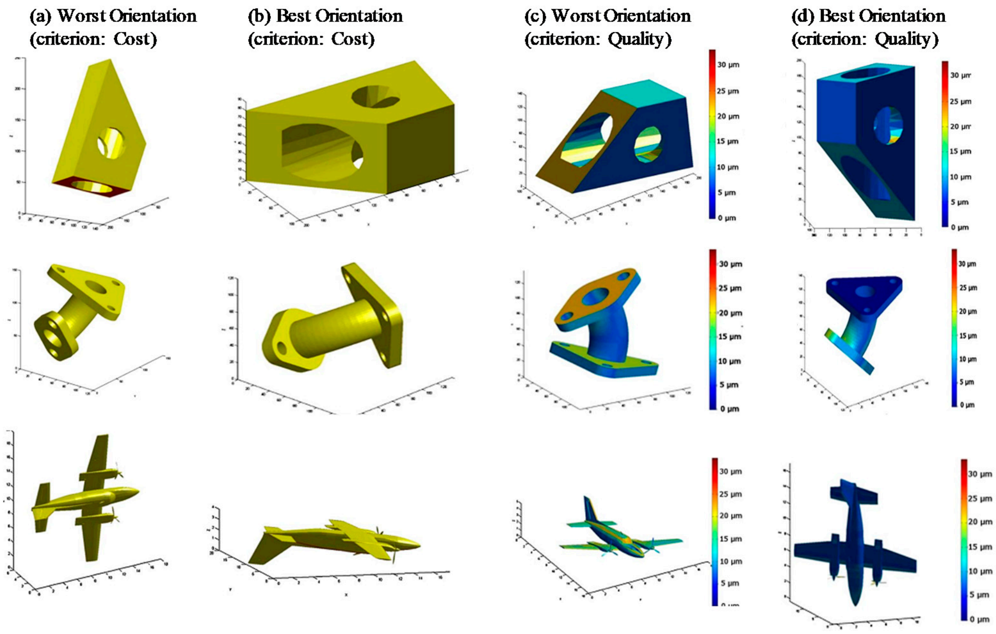

Figure 9. Isometric views of computed orientations for the (Figures reused with permission from [179]): (**a**) worst fabrication cost, (**b**) best fabrication cost, (**c**) worst surface quality, and (**d**) best surface quality of the three different models.

2.5. Part Complexity

Artists, artisans, and industrial designers use AM processes to create complex aesthetic, functional, economic, emotional, and ergonomic products because of their ability to create unique freeform geometries. AM is used to create complex products in jewelry production [180], home furnishing [181,182] (cantilever chair [182] (Figure 10a), and industry, robotic arm [183] (Figure 10b). One of the many AM characteristics is the creation of complex internal features to increase functionality in many applications, including integrated air ducts [184], 3D flexures of robot grippers [185] (Figure 11a), complex internal pathways for acoustic damping devices [186] (Figure 11b), internal micro-vanes for ocular medical devices [187] (Figure 11c), and the most widely applied conformal cooling channels [188,189] (Figure 11d).

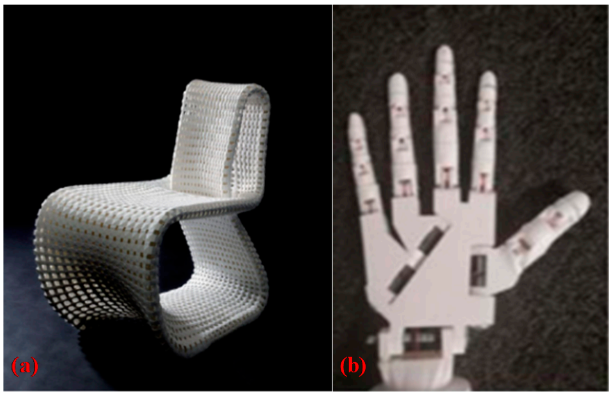

Figure 10. (**a**) Cantilever chair (Figure reused with permission from [182]), and (**b**) robotic arm (Figure reused with permission from [183]).

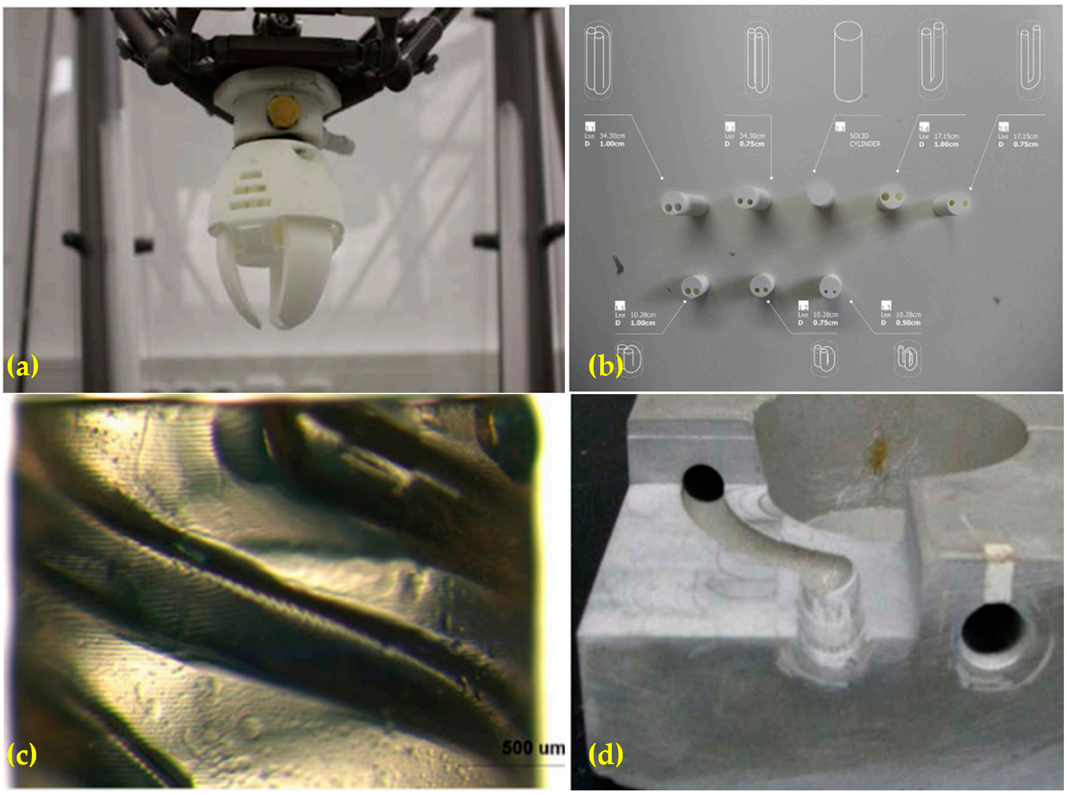

Figure 11. (**a**) Additive manufactured grippers for high-speed handling (Figure reused with permission from [185]), (**b**) different passive destructive interference absorbers PDI-absorber samples (Figure reused with permission from [186]), (**c**) optical micrographs of micro-vanes (Figure reused with permission from [187]), and (**d**) cut-away sections of circular conformal cooling channel mold cavities (Figure reused with permission from [188].

Embedded parts in printed parts are one of the AM capabilities that allow objects (e.g., cooling channels [190], NiTi fibers [191] (Figure 12a), shape memory alloys [190], batteries [192] (Figure 12b), electrical components [193,194] (Figure 13a–c), and sensors [195] (Figure 14a,b) to be embedded on the printed part. Khosravani and Reinicke [196] conducted a comprehensive review of the manufacturing of sensors using AM methods.

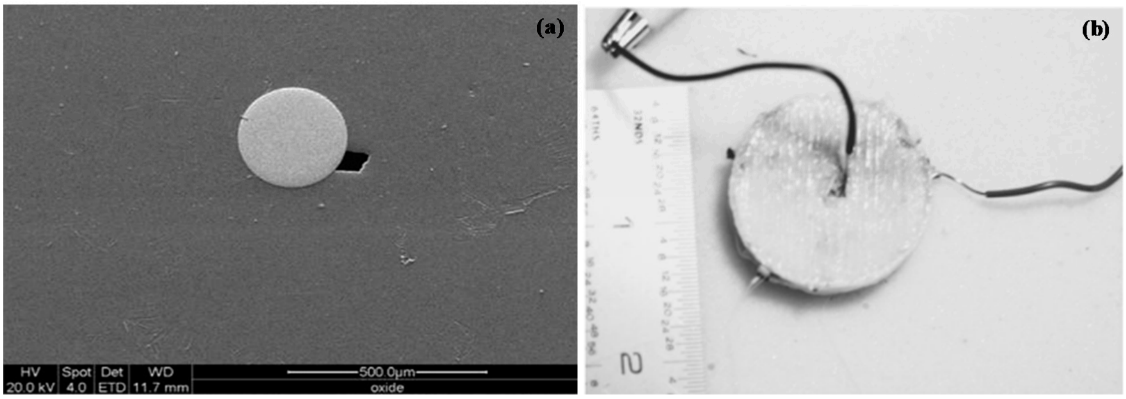

Figure 12. (**a**) scanning electron microscope (SEM) image of embedded NiTifiber (Figure reused with permission from [191]) (**b**) Freeform fabricated battery (Figure reused with permission from [192]).

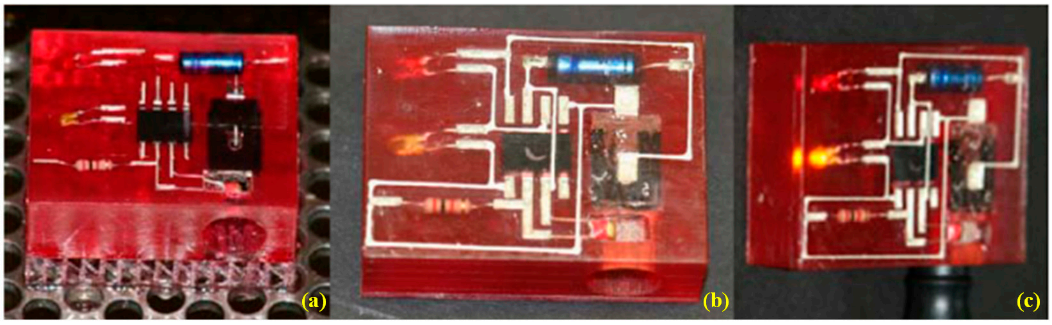

Figure 13. Examples of 3D electronics (Figure reused with permission from [194]): (**a**) stereolithography (SL) part with embedded components, (**b**) SL part with direct print (DP) interconnects, (**c**) final working circuit.

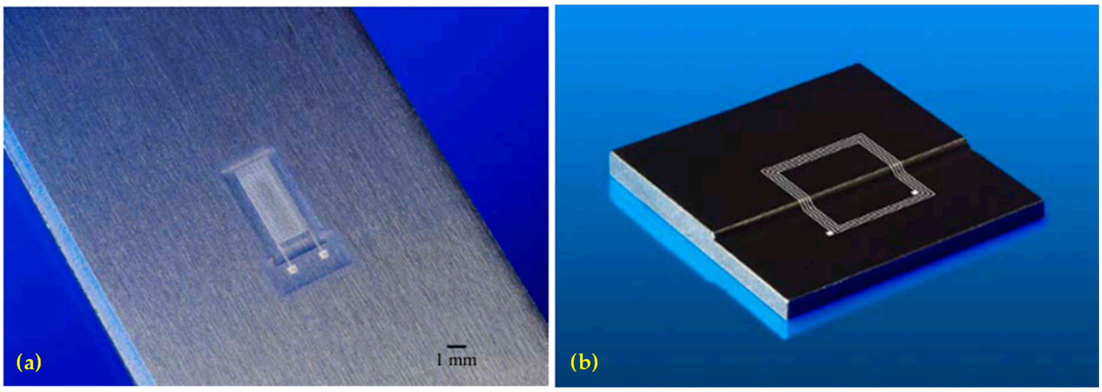

Figure 14. Embedded parts (Figure reused with permission from [195]): (**a**) Printed strain gauge on aluminum. (**b**) Aerosol-printed antenna on a non-planar surface.

2.6. Sustainability

The sustainability design considers the creation of goods, such that their economic and social effects are optimized, and the negative environmental effects are eliminated or reduced. AM can produce sustainable products that meet the economy, environment, and societal requirements [4]. AM's sustainability strategies include producing durable products, using recycled materials, adapting high-efficiency manufacturing methods, eliminating/reducing the use of hazardous materials, and constructing a deep connection between the product and the consumer. Figure 15 summarizes all aspects of the sustainability of AM processes based on three main dimensions (i.e., economic, environmental, and social dimensions) [197].

Sustainability of Additive Manufacturing				
Economy	Environment			Society
o Market Evolution	Resource consumption	Waste Management	Public Control	o Social Benefits
o Novel Applications	o Materials Demands	o Recyclable Waste	o Process Emissions	o Labor Development
o Supply Chain Management	o Process Energy	o Non-recyclable Waste		o Product Quality
o Production Costs	o Life Cycle Energy		o Life Cycle Emissions	o Public Acceptance
o Materials Costs				o Healthcare Improvements
o Machinery				o Ethics
o Process Productivity				o Copyright and Patents

Figure 15. Three aspects of impact in the context of AM sustainability (Figure reproduced with permission from [2]).

Medellin et al. [4] defined the DfAM strategies for sustainability in FDM processes as part cost, energy consumption, and environmental resistance. Taddese et al. [198] classified a comprehensive literature review on sustainability performance indicators for additive manufacturing. They classified the sustainability performance indicators into the environment, economy, and social. The environmental indicators were defined as the input and output resources, which are the major sources of environmental impact, such as part and support material, energy, water, biodiversity, emissions, and transport. The economic indicators were measured through economic viability, market presence, and indirect economic impacts. The overall economic performance is related to the overall cost minimization and improved value of the product throughout its life cycle. The social sustainability dimension considers the aspects of employees, consumers, and the surrounding community. Mehrpouya et al. [199] discussed the sustainable benefits of AM, sustainable design of AM, and sustainability assessment.

Bourhis et al. [200] developed a methodology based on analytic and experimental models to assess the environmental impact of consumed materials, fluids, and electricity. Meanwhile, Yang et al. [127] developed a detailed understanding of the environmental performance of the PC design for improved sustainability and provided decision support in choosing the PC procedure rather than the assembly design procedure.

3. Discussion

This overview explored some of DfAM's key design opportunities and applications and illustrated what is feasible and affordable today. The DfAM is still in its infancy, and an understanding of when and how to design AM is still lacking. Many of the technologies needed to support AM are still not developed. This paper discusses some of the guidelines and opportunities that DfAM offered.

3.1. DfAM Guidelines

The design and production stages during the new product development process are important because any decision at this stage can directly affect the cost and quality of the final product. The literature recommends basic principles and design guidelines, such as the design for X, to support designers in this decision-making process. These design guidelines focus on manufacturing, assembly, minimum risk, sustainability, standardization, prevention of corrosion, recycling, durability, materials, maintenance, and minimum costs, among others [4]. In terms of the production design, the current guidelines only consider conventional manufacturing methods, such as joining, casting, machining, forming, processing of materials, and finishing [201,202].

Common guideline can be summarized as follows: the inclination angles of overhang parts should be greater than a given lower bound angle, self-supporting angle varies depending on the material, but it is typically around 45 degrees [203]. Overhang with small inclination angle can make removal of the supports difficult. Removal of the support structure greatly reduces the surface finish and requires post-processing [3,126]. Hollowing out parts (if functionally accepted) leads to reduced printing time and material utilization [120,204,205]. Interlocking features can be used to link parts in cases of assembly difficulties [206] or large parts are required to be divided as AM has limited building space [126]. The reduction of part count leads to reduce the assembly time [120,126,207].

For post-processing, the machining allowance should be considered when dimensional accuracy is required.

To obtain the full benefits of AM, designers should learn to think differently with a focus on creating powerful and value-added industrial solutions. Design theories, methods, tools, processes, and techniques [208] should be developed to deal with the inherent association between geometry, materials, and quality in these systems. Customized implementation tools must be developed to support the design of cellular structures, heterogeneous artifacts, materials, biological scaffolding [209], etc. In addition, each build should always be identified as a design object with its own requirements and characteristics (e.g., parts layout and support structures) to be designed and improved.

3.2. DfAM Tools

The development of tools, theories, methods, and processes must be compiled and made available in the educational and industrial fields. Several DfAM methods have been proposed, thus different computer-aided programs have been developed. These tools include the geometric modeling-based design [210], evolutionary algorithm-driven design [211,212], and theory-driven design methods (topology optimization) used in design representation, analysis, and optimization [211]. These tools provide the initial design (Solidworks (Dassault Systèmes, Bellevue, WA, USA), Fusion 360 (Autodesk, San Rafael, CA, USA), and Rhino (Robert McNeel & Associates, Seattle, WA, USA)) [213,214], generate and optimize support structures (bio-inspired generative design method [19], polygon-featured holes method [21]), optimize build orientation (Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method [215], multi-objective particle swarm optimization (MOPSO) algorithm [216], genetic algorithm (GA)-based strategy [204]), perform the DfAM analysis and weight reduction (the inherent strain method [217] and automatically distribute materials within a given design domain (Medial Axis Transform (MAT) [218]).

To overcome the constraints embedded by the AM processes, there are some tools reported by previous studies. The multiresolution topology optimization (MTOP) method has been applied to suppress the thin poles present in the optimized design to some extent, as well as to suppress the 3D hanging features without any additional effort [19]. The polygon-featured holes method has been utilized to remove the sacrificial support materials comes at the cost of increasing structural, as well as to control the structural topology [21]. An efficient structural connectivity control (SCC) approach used in order to remove the enclosed voids which prevent the removal of unmelted material/support structure, it would find a potential path of connection the voids with structure boundary [23]. The quasi-static thermo-mechanical (QTM) method has been utilized to predict the thermal stress and distortion of part produced by AM [24]. The three-dimensional topology optimization algorithm can minimize the cost and time of AM-produced parts [26]. The Fused Filament Fabrication methods have been applied to improve the induced anisotropy in material properties at the same time its robustness and lightness [25].

4. Conclusions

This paper presented a comprehensive review of the DfAM strategies. Consequently, a detailed set of designs for AM approaches was presented based on the opportunities and applications of current AM technologies and systems. The proposed DfAM strategies are classified as follows into seven main categories: cellular structures, consolidation and assembly of parts, materials, support structures, build orientation, part complexity, and product sustainability. The DfAM approaches are designed to assist designers in making design decisions to meet functional needs, ensuring manufacturability in AM systems, and helping manufacturers during part fabrication in AM systems. Designers should learn to think differently with a focus on creating powerful and value-added industrial solutions to obtain the full benefits of AM. Design theories, methods, tools, processes, and techniques should be developed to deal with the inherent association between geometry, materials, and quality in these systems.

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