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Editorial

Design for Additive Manufacturing: Methods and Tools

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1. Introduction

Additive Manufacturing (AM), one of the nine enabling technologies of Industry 4.0, is experiencing rapid growth. Nowadays, there are no industrial sectors that have not employed AM (e.g., automotive [1], energy [2], medicine [3,4], electronics [5], cultural heritage [6]). Nevertheless, the implementation of technologies by industries is still limited compared to their intrinsic potential. The main challenges that limit the adoption of such technologies are lack of skills (need to train engineers capable of designing and managing these new technologies), sustainability of new processes (need to develop cost and environmental models capable of considering economic and environmental sustainability of AM processes and related supply chain) and design (need of innovative design paradigms and Design for Additive Manufacturing–DfAM–software tools).

ASTM ISO/ASTM52910 [7] gives requirements, guidelines, and recommendations for using AM in product design. This regulation helps determine which design considerations can be utilised in a design project or to take advantage of the capabilities of an AM process. The overall DfAM strategy presented in Figure 1 is the lighthouse for other methods conceived for specific problems and products [1,7–11].

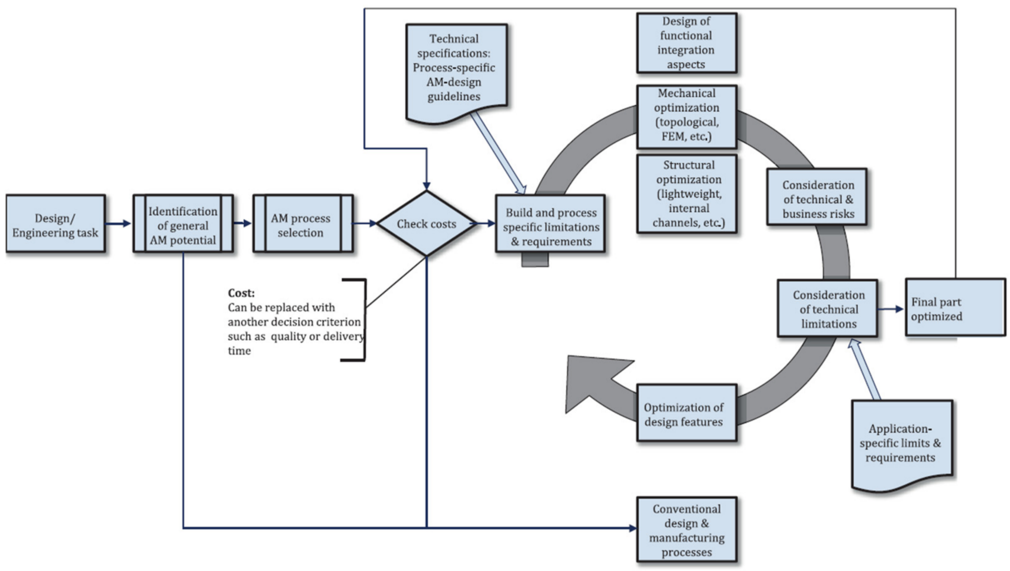

Figure 1. Overall strategy for design for AM, ISO/ASTM 52910 [7].

In recent years, DfAM software tools quickly advanced, allowing for the prediction and thus optimising designs for manufacture [12]. In addition to the traditional CAD tools, the design freedom pushed software houses toward developing systems able to model organic shapes (a result of topology optimisation or generative design approaches). Simulation systems are increasingly supporting designers and production technologists in identifying problems before 3D printing (e.g., deformation, accumulation of tension, porosity) [13–15].

This editorial aims to highlight the current design methods and tools conceived for supporting the product development (from conceptualisation to detail design). The editorial refers to the Special Issue "Design for Additive Manufacturing: Methods and Tools" of *Applied Sciences* (MDPI). The paper presents some applications to evaluate better the benefits of what is available in the scientific literature. Future trends on DfAM methods and tools conclude the editorial.

2. DfAM Methodologies and Methods

The special issue covers different studies on DfAM methodologies and methods, with the majority focusing on developing and implementing Topology Optimisation (TO) for capitalising on AM opportunities. Ahmad, Bici and Campana [6] investigated how TO can be implemented as a concept design tool to conceive the inner supporting frame of an ancient statue. In this application, TO can close the gap between experts and young designers, supporting preliminary target evaluations and topology conception. Dalpadulo et al. [1] proposed a design methodology to optimise components by integrating TO into the redesign process for an AM Assistive Device. Their paper shows how TO can be integrated into a redesign process to achieve mechanical and AM Key Performance Indicators. The DfAM workflow proposed by Sotomayor, Caiazzo and Alfieri [10] integrates optimisation, design, and simulation tools to minimise the number of iterative design evaluations. The authors proposed introducing TO, lattice infill optimisation, and generative design in earlier phases of the design process to maximise AM capabilities. Rosso et al. [9] presented a DfAM workflow for embodiment design that combines Computer-Aided Design tools for the geometric modelling of the part and Computer-Aided Engineering tools for the optimisation and simulation phases. Their workflow considers the possibility of using size optimisation to obtain lattice structures with optimised beams and TO to obtain optimised organic shapes. Fu et al. [16] proposed a new element-based TO method based on Langelaar's AM filter to generate mechanically optimised and self-supporting designs for AM. The approach integrates restrictive DfAM constraints such as overhang angle and length to create support free designs and reduce post-processing costs. Finally, in their review of TO in the design of steel structures and components for AM, Ribeiro et al. [17] examined the methods, applications and research trends of TO in civil and structural engineering over the past five years.

Alongside TO, the remaining authors studied a range of DfAM methodologies and methods. Raffaeli et al. [8] proposed a systematic approach to support designers in understanding the opportunities offered by AM in the design of machined parts. The approach implements multi-criteria decision making to systematically assess the suitability of AM for a given set of design requirements. The study demonstrates that this approach can be advantageous, especially in the early stages of the design process. Rolinck et al. [11] presented a holistic design and development methodology for hydraulic manifolds and fluid components with improved product performance and optimised for Laser Powder Bed Fusion (LPBF). Lastly, in a comparative study, Ikeuchi et al. [14] developed a new artificial neural network model to create a data-efficient modelling approach for simulating cold spray additive manufacturing. The model can predict an as-fabricated product allowing designers to understand the economic and environmental impact of design decisions on material waste after post-processing.

3. DfAM Tools

AM process allows realising parts with highly complex shapes that are impossible to produce by any other technologies. The complexity and variability of the additive processes require advanced design tools to optimise the product geometry and the settings of the machine parameters.

The completed design workflow of AM parts requires different kinds of software and the employment of highly skilled users. The specific design tools concern the CAD modelling of the geometrical details, the Finite Element Method (FEM) analysis to simulate the mechanical behaviour of the part after printing, and the FEM simulation of the phases of the 3D printing process, etc. The literature already shows several DfAM tools; however, the 3D printing process's complexity and variability limit the widespread of general purposes tools.

A completed review of Computer-Aided Engineering (CAE) tools for AM is proposed by Nieto and Sanchez [12]. Their work aims to maximise the vantages of AM technology by presenting the use of specific tools for product development. They analysed engineering and CAD platform tools such as mesostructured design, optimisation software, process management, and simulation solutions. Here, the DfAM tools are classified into seven categories: Design, Topology Optimisation, 3D mesh, Process Simulation, In-service Simulation, and Preprinting Slicing. These seven design tools are employed in five design AM phases: Design, Verification, Slicing, Printing, and Finishing. The most ambitious category concerns the simulation of the 3D printing phases because of the novelty of this manufacturing process. These simulations mostly regard the powder bed fusion processes, allowing geometrical deformations and residual stresses to be calculated. Therefore, the process simulations allow optimising the process parameters to minimise the accumulated tensions and the deformations of the pieces during and after printing. The designer can also use the simulation report to analyse the printing position, select the material, and optimise the support structures.

While some DfAM tools are well known in the scientific literature and community, others are new and exclusive for specific additive manufacturing phases and processes. For example, Kim and Kang developed a specific DfAM tool for Carbon-Fibers-Reinforced Polymer filament in Fusion Deposition Modeling (FDM) [13]. They implemented a tool-path algorithm to optimise the orientation of the fibres in the FDM process. The main idea was to reinforce fibres aligned with the profile of the high-stress region, which was previously calculated by FEM analysis. This DfAM tool can be classified in Preprinting Slicing, according to the classification described in [12]. Moreover, it can be employed in the phases of Design and Slicing.

Zouaoui et al. [15] described an example of a design tool for In-service Simulation. They developed a simplified Finite Element Method (FEM) to predict the mechanical behaviour of parts manufactured by fused filament fabrication (FFF) of polymeric pre-structured materials. This paper considers the filament orientation along with the principal stress directions. They also considered the anisotropy of the material related to complex deposition trajectories by introducing specific constants. The simulation confirms that the longitudinal loading direction has the highest yield strength than the transversal one for the FFF process.

The study of DfAM tools is still an open topic in research. They can be classified by objectives, design phase, materials, or processes; however, they are still so specific that they cannot be applied as general-purpose solutions in AM design. In this context, the literature shows relevant cases of these tools for enhancing their replicability in different applications.

4. Applications of Methods and Tools for Additive Manufacturing

AM, intended to integrate design software and 3D printing machines to complete the product's manufacturing [18], guarantees multiple benefits in Industry 4.0. The most significant are: customisation, design and development, prototyping, virtual inventory, reduced wastages, speed, flexibility, risk reduction, customer satisfaction, accuracy, productivity, improved profitability, improved supply chain performance, and cost reduction [18].

The variety of materials employed in AM processes (i.e., metals and alloys, polymers, composites, ceramics, and concrete) makes this technology applicable to several industrial sectors. The most trending could be summarised as follows [19]:

- *Biomedical and Biofabrication*: the biomedical market represents around 16% of the total AM market share (Wohlers' report). AM can guarantee the realisation of high-complex shapes [4,20] for innovative biomedical implants, organs, and controlled drug delivery systems. Open-source design methodologies can be used to quickly share 3D AM CAD files among researchers [3].
- *Aerospace*: this sector represents around 18% of the total AM market share. AM may allow the production of complex geometries resulting from parts consolidation, fluidodynamics simulation (to maximise efficiency [2]), and topology optimisation (to maximise the performance to weight ratio). Furthermore, functional electronics (e.g., resistive sensors) can be easily 3D printed [5].
- *Buildings, architecture, and cultural heritage*: this is an infancy sector expected to grow. AM can reduce construction time, increase geometry complexity, and reduce the consumption of heart resources. Reconstruction, documentation, and preservation are the typical AM purposes for cultural heritage [6].
- *Transport and automotive*: AM can produce lightweight components in this sector, which are increasingly requested to comply with energy consumption regulations. AM can also speed up the product development phase. For example, AM is currently adopted to realise soft assembly tools to increase productivity and manage customised parts without increasing production complexity and cost [21].

5. Future Trends in DfAM Methods and Tools

DfAM methods and tools continuously evolve to manage new production technologies and materials and support design engineers adopting AM. Among the future trends for this topic, hereunder are the most relevant to be addressed in future and specific research:

- Methodologies to support designers in disruptive/innovative rather than incremental design [22].
- AM for improving environmental sustainability. Methods to evaluate the environmental sustainability for multi-criteria decision making, product remanufacturing, etc. [22].
- Adopt Life Cycle Costing approaches to evaluate the sustainability of AM [22].
- Extend and update DfAM rules related to the emerging manufacturing technologies.
- Characterisation of complex lattice structures [23].
- Improved simulation software tools for accurately predicting product performances [23].
- Software tools to manage multiple materials, meta material design, multiple function design, and multi-scale [22].
- Knowledge-based 3D CAD systems to automatically model optimised AM shapes [24].
- Increase the adoption of AM and definition of DfAM rules for thermofluid, optical and electronic applications [22].

6. Conclusions

As emerged in this editorial, Additive Manufacturing is one of the most exciting research topics in the industry. New design methods and innovative software tools aim to support designers in considering this production edge-breaking technology during product development. The papers published in the Special Issue "Design for Additive Manufacturing: Methods and Tools" of *Applied Sciences* Journal entirely focus on this goal. Nevertheless, since the rapid growth of AM technologies and materials, design methods and tools should follow this trend to continuously support designers of the involved industrial sectors for applying AM and exploiting related unique benefits.

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