Analyzing Tools and Methods in Design for Additive Manufacturing: Workflow and Test Cases

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Abstract. Nowadays, Additive Manufacturing (AM) technologies are widely used in industry to produce customized parts. AM is chosen due to the many advantages of achieving generally more complex and lightweight geometries without a huge increase of costs in respect to "classical" subtractive manufacturing, reducing also the processing time. Materials employed can be plastics, metals, ceramics, composites, etc. The application fields regard the aerospace, automotive, and general-purpose industry. Design for Additive Manufacturing (DfAM) is the discipline that investigates the design tools and methods to be used in AM processes, including the tools for defining generative geometries and lattice structures with the support of simulations and optimization methods. Several design tools and methods can be applied during the Additive Manufacturing workflow. The paper analyzes the various tools and methods available in the literature, contextualizing them in the different phases of the design workflow. The objective is to provide guidelines while approaching the complexity of the AM design. Two different test cases are analyzed to check the proposed approach with different products, different materials, and different optimization methods. The two test cases regard the redesign of a horse saddletree and a diesel-engine connecting rod.

Keywords: Design for Additive Manufacturing, Lightweight Engineering, Optimization, Lattice Structure.
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1 INTRODUCTION

Nowadays, Additive Manufacturing (AM) technologies are widely used in industry to produce customized parts. AM is chosen due to the many advantages of achieving more complex geometries without a huge increase of costs in respect to "classical" subtractive manufacturing, reducing the

processing time. Employed materials can be plastics, metals, ceramics, composites, etc. The application fields regard the aerospace, automotive, and general-purpose industry. The development of the "Industry 4.0" paradigms is promoting the implementation of AM systems. They enable digital manufacturing since they 3D-print components starting from their solid models.
All AM processes are defined in the standard ISO/ASTM 52900:2022 [22]. Generally, each process has its advantages with its constraints, limitations, and fields of applicability. The 3D printing resolution and cost are some of the main limitations of the AM process. A high-resolution process improves the quality of the printed, enabling the printability of small details. However, the resolution is limited by the technology used and this issue introduces geometrical constraints during the design phase [18].

The employed material is another important parameter of the AM process. While some processes are specific to plastics, others are related to metals. The use of composites can reduce the limits of some technologies related to the low mechanical performance of plastics [21]. The mechanical performance of the built part is related not only to the material behavior but also to the final quality of the component (e.g. roughness for fatigue resistance, micro-voids for crack propagation and fatigue). There is a great interest in metal parts because they are employed in machines due to their properties of mechanical resistance, stiffness, thermal stress, etc.

Within the huge set of AM technologies, Laser Powder Bed Fusion (LPBF) is one of the AM processes used to produce metal parts with high resolution and high mechanical properties. This process enables the possibility of realizing complex geometries previously difficult or impossible to achieve. This capability influences design and redesign choices. The complex geometries can be various, such as lattice structures, organic shapes, internal channels, and geometries obtained from generative [6] and topology optimizations [3]. The ability to create lattice structures and hollow components enables the production of lightweight parts while still ensuring robustness. Designers can strategically remove material that is not structurally necessary, reducing weight and material usage without reducing strength. The mechanical behavior of the lightweight parts should be evaluated using numerical simulations. In the context of AM, the redesign process also enables the fabrication of assemblies as a single part, consolidating multiple assemblies into a single unit. This activity reduces assembly time, minimizes the need for fasteners, and eliminates potential points of failure, leading to a simpler and more efficient design. However, the cost of the process and powders limit the use of metal AM technology. One of the solutions is the study of geometries easy to be printed. Another solution is the use of recycled powders. Lightweight Engineering is a good practice to reduce the material cost while providing the necessary mechanical behavior [10].

Design for Additive Manufacturing (DfAM) is the discipline that investigates the design tools and methods to produce parts using AM processes [29]. DfAM also includes tools for defining generative geometries and lattice structures with the support of simulations and optimization methods. DfAM promotes exploring new solutions to overcome the limits of the process. Several redesign activities are described in the literature [11,16,27]. These examples confirm that DfAM practices can improve product quality (such as tolerances and reliability) and cost reduction.

The DfAM activities are complex and require various methods and tools due to the high number of processes and their related parameters. The paper proposes a general design workflow that highlights the main design steps for completing a redesign process. The redesign of components often aims at reducing the final weight of the optimized part. The scope of the research is to provide guidelines while approaching the complexity of the AM. The paper also proposes two test cases to analyze the redesign of a horse saddletree and a diesel-engine connecting rod.

2 METHODOLOGICAL WORKFLOW

The following section outlines the proposed workflow for designing parts that will be produced using AM. Figure 1 illustrates the proposed workflow, highlighting the main phases and their respective specifications. The process begins by defining the reference model, then, it continues with the application of one or more optimization practices, and ends with the simulations of the AM process.

A detailed description of each phase is provided below. The presented workflow aims to support the designer in all phases of DfAM, from the early design phase to models ready for 3D printing, using different tools. The method also describes the connections between each design phase.

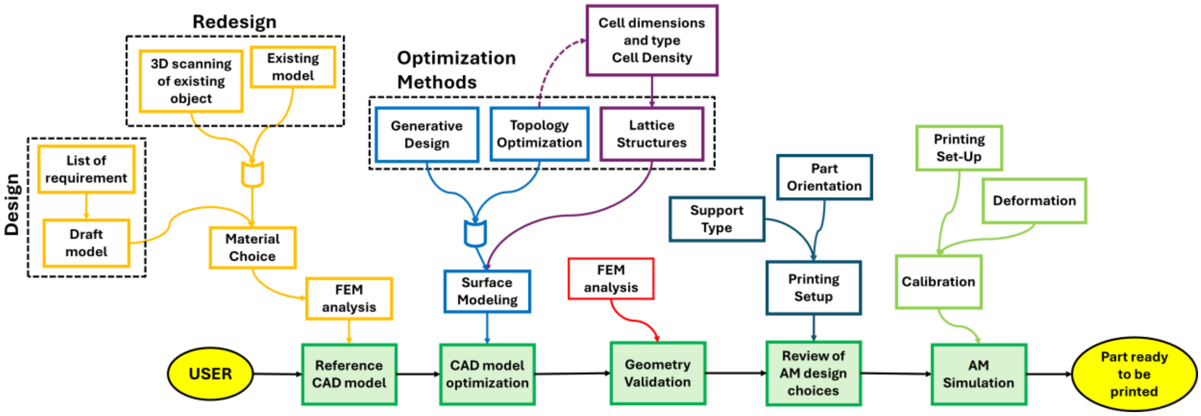


Figure 1: The proposed design workflow for parts to be realized by AM processes.

2.1 Reference CAD Model

A starting CAD model to be used as a reference is necessary to begin a design activity for AM. If the part already exists, the CAD file could be available. Otherwise, a draft model can be modeled using CAD software. This reference model will be a conceptual model to be used in the early design phases. If a physical part exists but the CAD model is not available, the modeling phase can be supported by a 3D scanning system which produces a digital point cloud of the part.

To start with the design activity, the mechanical behavior of the reference CAD model should be evaluated. Generally, Finite Element Methods (FEM) tools are used to simulate the mechanical behavior. This phase requires the definition of the material properties and boundary conditions such as operative temperature, loads, constraints, etc. The results of the numerical analysis give information about the distribution of stress and deformation on the reference model, highlighting the points to be improved. The analysis of the results is an essential phase to define the objective functions for the optimization analysis.

2.2 CAD Model Optimization

The phase of CAD model optimization includes optimization methods oriented to achieve improvements in structural design, using Topological Optimization, Generative Design, or Lattice Structures.

2.2.1 Generative and Topology methods

The design optimization of the reference model can be performed using tools and methods such as Topology Optimization and Generative Design. These methods use the numerical results of the FEM tools, both can be applied to generate alternative solutions according to boundary conditions, objective functions, and geometrical constraints. The objective functions lead the optimization analysis and the search for optimal solutions.

Topological Optimization supports preliminary design by modeling the design space in accordance with the boundary conditions defined in the non-design space [3,8]. While the design space is the body of the reference CAD model previously defined, the non-design space is the collection of the geometries that the Topological Optimization algorithm cannot modify. These geometries can be the surfaces where loads and constraints are applied (boundary conditions). The theoretical bases for Topological Optimization are SIMP or Level Set Method [28], now implemented in both general-purpose commercial FEA and optimization AM design software.

Generative Design is a design methodology that adopts CAD-CAE modules to define design alternatives from a set of optimization goals (e.g. final weight, stress, compliance, manufacturability, ergonomics, etc.) and parametric design variables. Topological Optimization is indeed one of the CAE modules suitable to explore the design space, together with product-process optimization, multicriteria optimization, or genetic algorithms are possible approaches to explore the optimal domain [6,12]. According to [26], Generative Design seems extremely suitable for the set-up conceptual design of new products, since it considers a simplified design space that includes only geometries to be connected (avoiding obstacles), so that the optimization algorithm may generate the connection of these geometries by adding material.

An issue related to topological optimization and generative practices is the necessity to smooth the resulting surfaces. Modeling changes from topological optimization are presented as FEA mesh that must be converted into a 3D model after a proper smooth and surface reconstruction, since lack of symmetry or small regions may be present because of mesh dependency of the optimization step. Therefore, a back-to-CAD activity is necessary to obtain a geometrical reconstruction, useful to continue the steps of the design workflow.

2.2.2 Lattice Structures

Lattices are three-dimensional structures where a basic element, the Unit Cell, is repeated within a defined volume through patterns. Lattice cells may have many different topologies. Figure 2 reports the classification of lattice structures, as defined in [1]. In recent years, several novel methods have been studied to customize the cell distribution and geometry in different zones of the volume, ensuring a better use and distribution of the material and a higher level of performance.

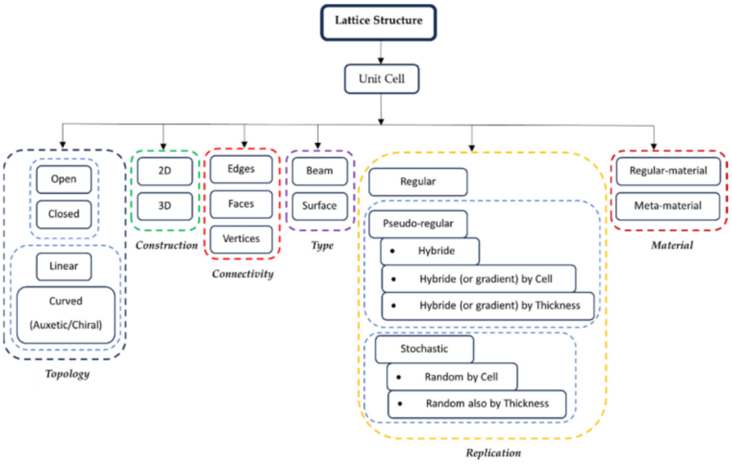


Figure 2: Classification of lattice structure [1].

A unit cell can be Struct-based or Triply Periodic Minimal Surfaces (TPMS) [20]. A struct-based Unit cell is characterized by several topological features depending on its founding struct element (i.e. beam) like thickness, length, spatial orientation, and interaction between them, thus many kinds of the cell can be used. Some Struct-based cells are reported in Figure 3.

On the other hand, TPMS unit cell topologies are generated using mathematical formulae that define the iso-surface boundary between solid and void sections of the structure (Figure 4). The pattern can be realized using different methods such as direct patterning, conformal patterning, and Topology Optimization [17]. In direct patterning, unit cell is repeated through translation, whereas conformal patterning allows to repetition of the unit cell adapting to the geometry of a selected surface.

Using lattice structures is a powerful method to reduce material quantity and obtain lightweight components, maintaining the part functionality. It is possible to identify two distinct ways for the lattice structures realization. The first method involves manually replacing a portion of the starting volume with these structures, deciding the type of cell, the density, the cell distribution, etc. The second method uses the results of specific algorithms such as the topology optimization (density map) as a starting point for the lattice structure creation, increasing or decreasing the density of the cells or the thicknesses of the cell components following the mechanical behavior required.

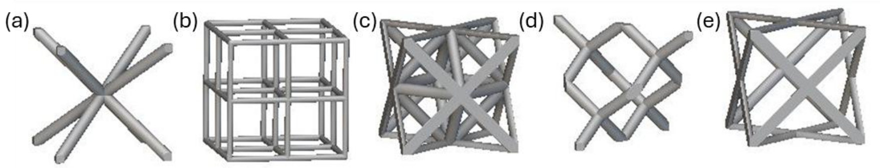


Figure 3: Example of Struct-based cells used for lattice structures: (a) BCC; (b) cubic; (c) octet-truss; (d) Diamond; (e) FCCZ.

Topological Optimization algorithms lead to multigraded distributions of densities (in a conformal way, as described in [9,14]. In the case of lattice structure, Level set methods demonstrated their capability to assess the goal, with major benefit in terms of computational efforts [19], since through implicit geometry it may tackle the mesoscale modeling of the cell more efficiently. Then, lattice beams, or surfaces in the case of TPMS, may be further optimized by shape optimization in terms of parametric distribution of radius or thickness [7,13]. From the material point of view, reliability of metallic components is still under investigation, as well as process sustainability or, more generally, from a lifecycle cost analysis point of view.

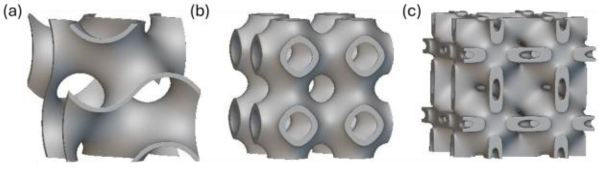


Figure 4: Examples of TPMS cells: (a) Schoen gyroid; (b) Schwarz diamond; (c) Neovius.

In L-PBF technology, the mechanical properties of lattice structures depend on material, architecture, and porosity [17]. The material affects the basic mechanical properties such as elastic modulus, yield strength, fragility, ductility, fatigue limit, etc. Their values are a fraction of the basic material ones. The architecture instead affects the mechanical flexibility of the structure. These properties depend on the relative density of the lattice structure, representing the ratio between the density of the lattice and the density of the bulk material.

2.3 Geometry Validation

The resulting geometrical models, analyzed in the optimization phase, need validation before continuing with the AM job. Following the paradigm of virtual prototyping, the validation activity is based on numerical simulations, using FEA tools.

One of the issues of this phase is the proper meshing of the FEA model. In fact, the geometrical bodies to be meshed come from practices such as topology optimization, generative design, and lattice structures, or their combinations. Therefore, the models could have a high number of small surfaces, difficult to be approximated by meshing elements. In the case of lattice structures, the issue of meshing small surfaces can be faced using a homogenization approach. This approach simulates the mechanical behavior of one cell and replicates it to each node of the lattice structures. The homogenization approach is fast but introduces approximation errors.

Boundary conditions analyzed in the validation phase are the same analyzed to reproduce the behavior of the reference CAD model. The material properties can be different because they are related to the final design choices. The simulation activity can regard numerical solvers for structural, thermal, modal, and other analyses. Under working conditions, the new product, to be realized by AM, must provide the necessary mechanical performance. It is not always feasible to utilize lattice structures when dealing with high loads and limited deformations to ensure proper system functionality.

2.4 Review of the AM Design Choices

The output model of the previous optimization analysis improves the mass distribution of the part, achieving a lightweight solution. However, the resulting geometry must be analyzed and validated to better align with the guidelines of the AM process. DfAM tools and methods support the implementation of these guidelines. Designers must consider factors such as part orientation [16] and types of support structures to be involved. These factors affect the overhang angles, building time, material quantity, and quality of the printed parts. Other considerations must be made for shapes that often cause problems during the printing phase. These shapes are minimum wall thickness, minimum and maximum hole clearance [24], too large extension of flat surfaces [15], concave hull [27], etc. Therefore, a Knowledge Base could support the geometry checks and compliance with the process guidelines and constraints.

2.5 AM Simulation

L-PBF process parameters can vary depending on factors such as the material being used, the geometry of the part, and the specific machine being utilized. Common process parameters are laser power, scanning speed, layer thickness, hatch distance, build chamber temperature, etc. [4]. These parameters can be evaluated during the design phase.

The simulations of the AM process are useful tools to investigate the results of the 3D printing phase, avoiding defects and reducing time and costs. L-PBF is an expensive process due to trial-and-error procedures in material usage and machine time. Simulations allow engineers to predict outcomes, reducing the need for physical prototypes and minimizing material waste. By simulating the L-PBF process, engineers can optimize process parameters to achieve the desired mechanical properties and minimize defects like porosity, distortions, and residual stresses. Simulations help in validating the design of complex parts before manufacturing, ensuring the realization of components without compromising structural integrity or functionality [5].

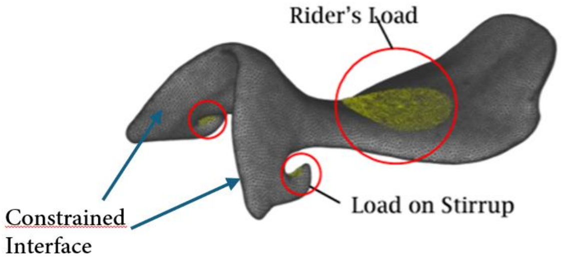
3 CASE STUDY 1

The first test case proposed describes a lattice-based optimization approach to the lightweight design of a horse saddletree [2]. The traditional horse saddletrees have a structure made of wood with steel inserts or synthetic materials; the covering of the horse saddles includes leather and other materials.

In this test case, a plastic material is considered to redesign the optimized inner structure of the saddletree in the AM process. Figure 5 reports the comparison between a traditional horse saddletree made of many components (Figure 5.a) and the optimized one to be 3D printed by a selective laser melting process (Figure 5.b), using a bio-derived powder material (Ultrasint® PA11 black CF), suitable for applications that require not only high strength, but also stiffness and resilience. The test case is a redesign problem faced starting from the Reverse Engineering of the dissected saddle, as reported also in [2]. The optimization was carried out by nTopology. Some of the boundary conditions are described in Figure 5.c: the rider's load, the load on the stirrup, and the constrained interface, which is the contact with the horse's neck.

(a)

(b)



(c)

Figure 5: (a) traditional wood saddletree with metallic inserts highlighted in red; (b) Final lattice structure design; (c) Load and Constraint sets [3].

The reference CAD model has been optimized using a topology optimization approach by a stochastic lattice with multigraded density, defined by a Voronoi distribution.
The adoption of the lattice together with the change of material and the reduction of the number of components allow an overall reduction of mass of more than 70% (0.47 kg versus 2 kg) to be achieved considering the comparison with a wood saddletree. In a comparison with an injection-molded saddletree, the weight reduction is about 30%.

This test case also considers the sustainability of the product in the redesign choices, reducing the material involved and introducing a bio-derived powder material as an alternative to wood saddletree. The wood saddletree involves a long manufacturing process with lamination and thermal treatment to achieve the proper shape and stiffness [23].

4 CASE STUDY 2

The second test case considered describes the design of a connecting rod to be printed in Ti6Al4V using L-PBF. The boundary conditions considered for the structural simulation in operation are reported in [25]. The studied connecting road refers to a 1.6-L diesel engine. The steel connecting roads of this engine are in 39NiCrMo3 with a weight of 0,670 kg. The lightened model for the 3D printing process achieves a final weight of 0,294 kg considering Ti6Al4V. Figure 6 shows the workflow related to this test case.

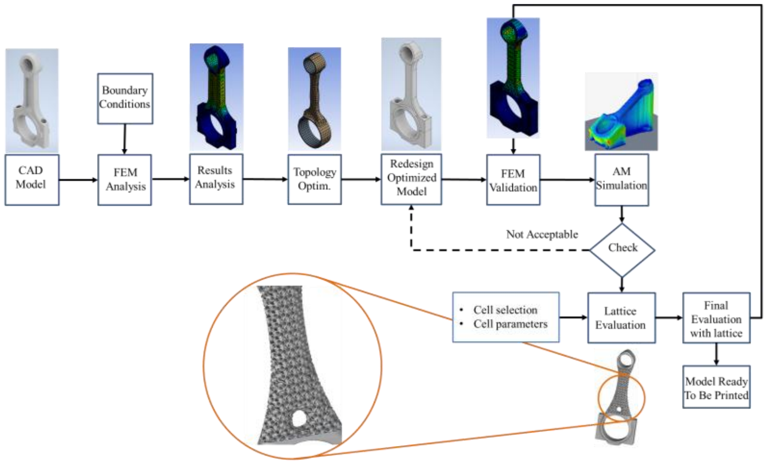


Figure 6: Description of the connecting rod test case.

Figure 7(a) shows the application of lattice structure on the topological-optimized connecting rod. The lattice structure cell is a gyroid-type unit cell, dimension of 5 mm x 5 mm x 5 mm, and an approximated thickness of 0.75 mm. The gyroid-type lattice structure allowed a further weight reduction to be achieved, obtaining a total final weight of 0.206 kg.

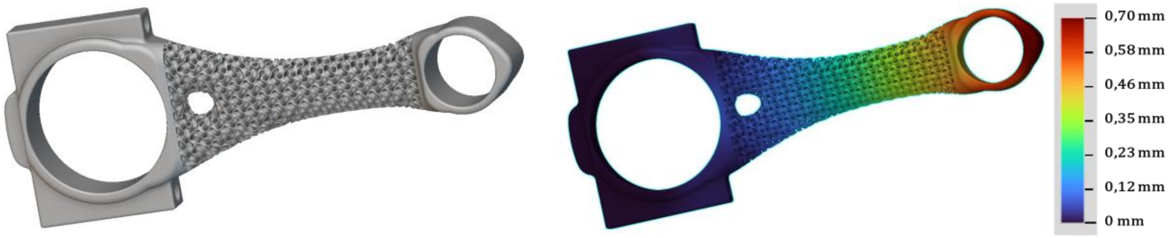


Figure 7: (a) Lattice application on the topological optimized connecting rod test case; (b) Displacement field as a report of the simulation performed in the validation phase.

Figure 7(b) shows the displacement field obtained via FEM analysis during the validation activity. The load case related to this analysis refers to the tensile force applied at the small end [25]. This load case generates greater tensions, compared to the design cases provided for connecting rods [25], and it exceeds about 67% of the maximum tensile strength for the chosen material. The use of lattice structures allows the weight of the part to be significantly reduced; however, in this case study, the analyzed lattice structure shows excessive deformation under the working conditions. Therefore, the study continues analyzing the geometry without lattice structure. The subsequent 3D printing study is related to the connecting rod optimized through topological optimization, which is the model capable of resisting boundary conditions.

The 3D printing simulations in this test case were performed using Altair® Inspire™ software. Figure 8(a) shows the 3D printing set-up for the AM simulation, highlighting the orientation and support structures. Figure 8(b) describes the simulated displacement field after the 3D printing phase. The values of stress and deformation achieved in this virtual test were considered acceptable, so the connecting rod is ready to be printed.

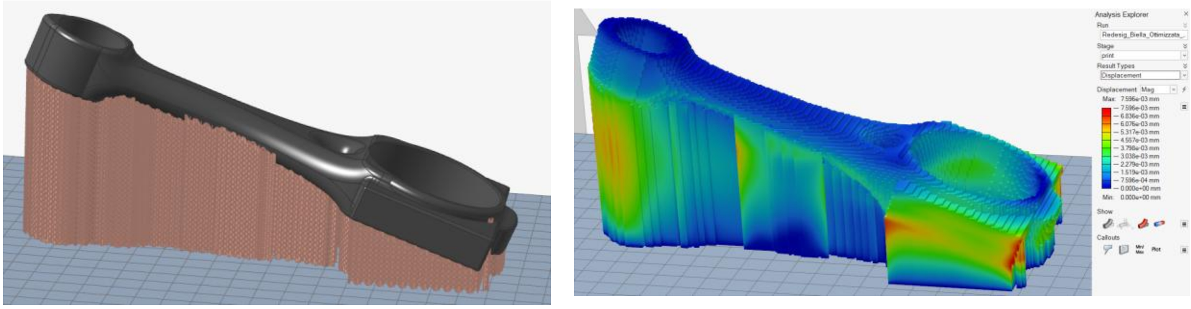


Figure 8: (a) orientation and support structures for the part to be analyzed; (b) AM simulation: displacement field after the 3D printing phase.

5 CONCLUSIONS

The paper proposes a workflow to support the redesign of parts to be realized by AM processes. The design approach investigates the optimization of the reference CAD models, using techniques such as Topology Optimization, Generative Design, and Lattice Structures or a combination of those. The approach also considers the phases of the geometrical check, structural simulations, and AM-process simulations. The objective is to provide designers a guideline to support all design phases of the redesign process. Optimization methods tend to reduce the quantity of material where it is not necessary, according to boundary conditions. These processes, if applied sequentially, may not guarantee the mechanical performances necessary. The geometrical check and structural simulations are relevant and fundamental for parts that require precise mechanical tolerances to ensure the correct functioning of the overall system. The AM-process simulations are a helpful tool for assessing the AM design, reducing the use of physical testing with a benefit in terms of cost and time.

Two test cases are reported to describe the results achieved in different applications related to the lightweight design of AM components. The first one shows the application of lattice structures on the design optimization of a horse saddletree. Considering a 3D-printing process with a bio-derived powder material (Ultrasint® PA11 black CF), the weight reduction is about 70% if compared with the use of a wood-metal saddletree that also asks for assembly of stir-up metallic elements. The second one is focused on the redesign of an automotive connecting rod. Considering the L-PBF process and Ti6Al4V powders, a weight reduction of about 50% has been achieved using the proposed approach. A model with a lattice structure and a weight reduction of about 67% has been also analyzed, however, this model did not pass the structural test. The study of the new connecting ends with the evaluation of the AM job with supports, orientation, and AM-process simulation.

AM processes show several advantages such as the possibility of achieving complex geometry and optimizing the material involved. However, a design workflow and a set of tools are necessary to manage the complexity. As future developments, the cost analysis and the Life Cycle Assessment will be introduced in the design workflow.

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