Title:

Design for Additive Manufacturing: A Workflow to Support the Redesign Phases

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Introduction:

Nowadays, Additive Manufacturing (AM) technologies are widely used in industry to produce customized parts. AM was chosen due to the many advantages of achieving complex geometries and reducing processing time. Materials employed can be plastics, metals, ceramics, composites, etc. The application fields regard aerospace and automotive and the general-purpose industry. The development of the "Industry 4.0" paradigms is promoting the implementation of AM systems. This technology enables digital manufacturing since there is a close link between the 3D modeling and the 3D printing.

All AM processes are defined in the standard ISO/ASTM 52900:2022 [13]. 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. The resolution also affects the geometrical constraints during the 3D part modeling. The impact of the process on part modeling is well-known in the scientific literature. 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 plastic. 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., and also due to the changes in these properties related to additive manufacturing parameters (orientation, layer thicknesses, printing speed, raw materials or powders, etc.).

Laser Powder Bed Fusion (LPBF) is one of the most used AM processes, and it is able 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 [2]. 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 and research of easy-to-print geometries. Another solution is the use of recycled powders. Lightweight engineering is a good practice that reduces the material cost while providing the necessary mechanical behavior [7].

Design for Additive Manufacturing (DfAM) is the discipline that investigates the design tools and methods to produce parts using AM processes [18]. DfAM also includes tools for defining generative geometries and lattice structures with the support of simulations and optimization methods. The paper analyzes these methods and tools, describing a design workflow with the objective to provide guidelines for engineers while approaching the complexity of the metal AM.

Method:

This section describes the proposed workflow for designing and re-designing parts to be produced in AM. Following, a description of each phase is reported.

The 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, which can be converted in STL or other convenient format, useful to obtain a CAD model.

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 regions to be improved. The analysis of the results is an essential phase to define the objective functions for the optimization analysis.

Optimization of the reference CAD model:

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 [2]. 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), as well as other geometries and features of the component.

Generative Design is an alternative optimization approach to propose design solutions from the geometries related to the boundary conditions [6]. This approach generates different solutions; therefore, the selection of the design variant that best describes the new component among all the possible solutions is of considerable importance. The designer must select the best compromise between the process, product parameters, and the redesign objective (functionality, lightweight, cost, etc.) [8].

The review of the design choices for AM:

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 AM process guidelines. DfAM tools and methods support the implementation of these guidelines. Designers must consider factors such as part orientation [10] 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 features that often cause problems during the printing phase. These features are characterized by minimum wall thickness, minimum and maximum hole clearance [15], too large extension of flat surfaces [9], concave hull [17], etc. Therefore, a knowledge base could support geometry checks and ensure compliance with process guidelines and constraints.

Lattice structures:

To further reduce the weight of the studied model and the necessary powder quantity related to the AM process, lattice structures can be applied. Lattices are three-dimensional structures where a basic element, the Unit Cell, is repeated within a defined volume through patterns [1]. Therefore, designing lattice structures means selecting the unit cell, the pattern, and the volume to be filled. In this case, the lattice structure replaces the solid portion of the defined volume.

Unit cells can be Struct-based or Triply Periodic Minimal Surfaces (TPMS) [12]. A struct-based Unit cell is characterized by several topological features depending on its founding struct elements (i.e., beam), like thickness, length, spatial orientation, and interaction between them. Thus, many kinds of cells can be used. 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. The pattern can be realized using different methods, such as direct patterning, conformal patterning, and Topology Optimization [11]. In direct patterning, the unit cell is repeated through translation, whereas conformal patterning allows the repetition of the unit cell to adapt to the geometry of a selected surface.

In literature there are many applications of lattice structure to improve the mass distribution and resistance, or to tailor component performances in accordance with a specific lattice structure (e.g. Heuxetic components for crashworthiness, multigraded material) [1].

Geometry validation:

The resulting model, performed after the phases of topology optimization and lattice structure, should be validated with numerical simulations before proceeding with the conclusion of the 3D printing simulation and job. These simulations investigate the behavior of the part under the loads of the working conditions using FEM solvers. The problem interests the simulations of geometrical domains with lattice structures. It is not easy to mesh the portion of a solid related to a lattice structure. Several FEM tools propose a homogenization approach to replicate the mechanical behavior of one cell to each node of the lattice structures. This approach is approximate and can introduce errors in the evaluation. However, this approach can be applied faster.

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 for investigating 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 accurately, 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].

Case Study 1:

The first test case proposed describes a lattice-based optimization approach to the lightweight design of a horse saddletree [3]. The traditional horse saddletrees have a structure made in 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 define the optimized structure of the saddletree to be realized by AM process. Moreover, this test case also considers the sustainability of the product in the design choices. In particular, the type of optimization, the material selection and AM parameters are discussed in terms of optimization not only for weight reduction or design performance but also in terms of AM process efforts. The saddletree, when made of wood, involves a long manufacturing process with lamination and thermal treatment to achieve the proper shape and stiffness [14]. Fig. 1 reports the comparison between a traditional horse saddletree and the optimized one to be 3D printed by a selective laser melting process.

(a) (b)

Fig. 1: Saddle-tree test case: (a) wood solution with metallic inserts (highlighted in red) (b) Final lattice structure design [3].

Case Study 2:

This second test case 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 [16]. 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. The workflow of the test case focused on the redesign of the connecting rod is described in Fig. 2.

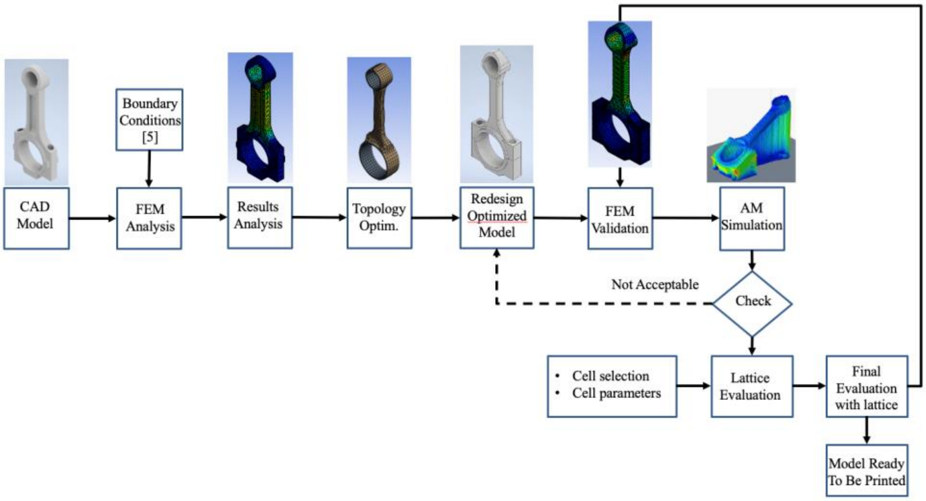

Fig. 2: Description of the connecting rod test case.

Conclusions:

The paper formalizes a workflow to support the redesign of parts to be realized by AM processes. The design approach uses optimizations of the reference CAD model, such as the topology optimization or the generative design, the review of the design choices from a DfAM perspective, the evaluation of the lattice structures application, the geometry validation, and the simulation of the additive printing process to reduce the waste of material due to issues during the printing phase. Two test cases are reported to describe the results achieved in different applications. The first test case shows the application of lattice structures on a horse saddletree, achieving a lightweight design. The second test case describes the design of a connecting rod to be printed in Ti6Al4V using the L-PBF technique.

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