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An Optimization Workflow in Design for Additive Manufacturing

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Abstract: Additive Manufacturing (AM) brought a revolution in parts design and production. It enables the possibility to obtain objects with complex geometries and to exploit structural optimization algorithms. Nevertheless, AM is far from being a mature technology and advances are still needed from different perspectives. Among these, the literature highlights the need of improving the frameworks that describe the design process and taking full advantage of the possibilities offered by AM. This work aims to propose a workflow for AM guiding the designer during the embodiment design phase, from the engineering requirements to the production of the final part. The main aspects are the optimization of the dimensions and the topology of the parts, to take into consideration functional and manufacturing requirements, and to validate the geometric model by computer-aided engineering software. Moreover, a case study dealing with the redesign of a piston rod is presented, in which the proposed workflow is adopted. Results show the effectiveness of the workflow when applied to cases in which structural optimization could bring an advantage in the design of a part and the pros and cons of the choices made during the design phases were highlighted.

Keywords: DfAM; design for additive manufacturing; size optimization; topology optimization; design workflow; computational geometry; geometric modeling

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Citation: Rosso, S.; Uriati, F.; Grigolato, L.; Meneghello, R.; Concheri, G.; Savio, G. An Optimization Workflow in Design for Additive Manufacturing. *Appl. Sci.* **2021**, *11*, 2572. https://doi.org/10.3390/app11062572

Academic Editor: Marco Mandolini

Received: 22 February 2021
Accepted: 11 March 2021
Published: 13 March 2021

1. Introduction

From the works of the early pioneers, additive manufacturing (AM) technologies were characterized by great growth in the last 35 years [1]. According to ISO/ASTM standards "AM is the general term for those technologies that, based on a geometrical representation, create physical objects by successive addition of material" [2]. Depending on the method of layer manufacturing, it is possible to organize the AM technologies in the following categories: vat photopolymerization, material jetting, binder jetting, powder bed fusion, material extrusion, directed energy deposition, and sheet lamination [2].

This technology brings new opportunities especially in design freedom, allowing very complex shapes, integrating cinematics and multi-material parts, reducing the number of components through part consolidation, and increasing mass customization. On the other hand, to fully exploit the AM technologies' potential, many needs in different sub-fields were highlighted [1,3–8], as summarized in Figure 1. For example, a highly skilled workforce is required, file formats for exchanging the data related to the AM workflow need enhancements [8,9], and design methods and tools for complex structures, multi-material parts, and functionally graded materials need to be improved [10,11]. The concerns over the structural integrity of these complex parts require static and dynamic mechanical characterization [12,13]; also, experimental tests help to mechanically characterize the materials, and the obtained information is used in numerical simulations to predict the different mechanical behavior between the products obtained through additive manufacturing and the ones obtained by traditional techniques of material subtraction [14,15]. More, dedicated qualification standards for AM are needed to guarantee an adequate quality of the printed parts [16,17] and their representation in 2D drawings [18].

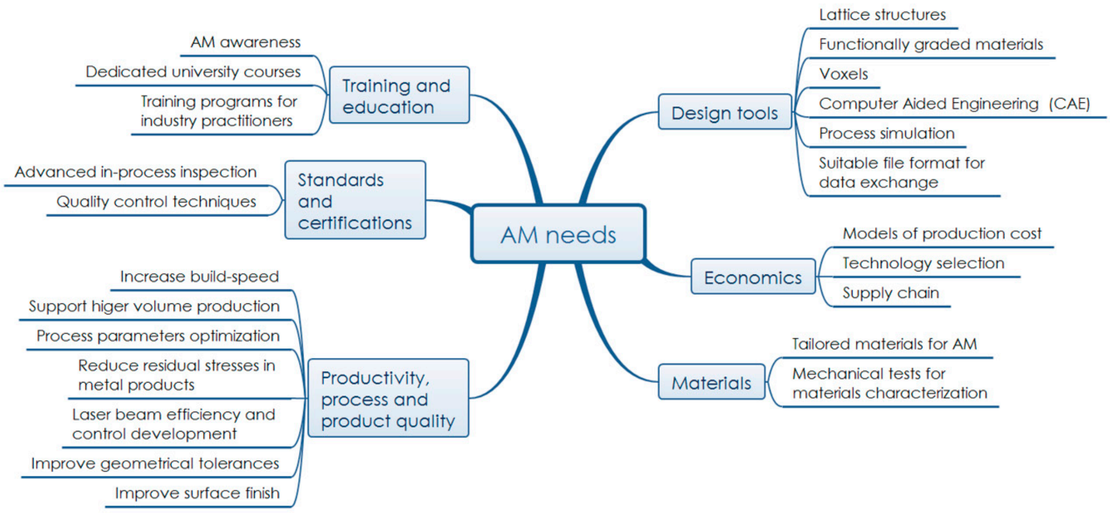

Figure 1. Additive Manufacturing needs.

In a recent work, *The Economist* claims that the value of AM products will no longer be in the physical item, but in its design [19]. These reflections lead to a reconsideration of the design approaches for AM. According to Ullman [20], the design process can be divided into six major phases: product discovery, project planning, product definition, conceptual design, product development, and product support. During the conceptual design phase, several concepts are generated and evaluated; however, the knowledge of the concepts is limited and the goal in this phase is to select the best alternatives with the least expenditure of time and other resources. In the product development phase, instead, once the product is generated, it is fundamental to compare its performance to the engineering specifications. This is done both with virtual simulations and physical prototypes, often resulting in a time-consuming iterative process due to part modifications and redesigns. A different approach that exploits the higher computational capabilities available nowadays is the computational design synthesis [21], where the tasks needed to obtain a solution are divided into four main steps: "representation" deals with the creation of a mental model of the object, "generation" deals with the object creation, "evaluation" verifies if the constraints and design goals are met, and "guidance" gives a feedback for the design improvements [22]. The last three phases are iteratively repeated until a final design is obtained. In design synthesis, optimization is performed in the representation and generation phases, where the design has not a specific topology yet. Usually, stochastic methods are applied to obtain different designs that satisfy the requirements [23].

Furthermore, when designing parts that are going to be produced by AM technologies, several thoughts must be considered to "maximize product performance through the synthesis of shapes, sizes, hierarchical structures, and material compositions, subject to the capabilities of AM technologies" [24]. All these considerations can be grouped within the Design for Additive Manufacturing (DfAM) concept. Gibson et al. [24] distinguished between opportunistic and restrictive DfAM; the former allows to take advantages of the unique capabilities of AM, such as cellular solids, part consolidation, and multi-material, whereas the latter focuses on the restrictions and limitations of the AM technologies, such as the minimum feature size and the need of support structures. Rosen [25] used a Process–Structure–Property–Behavior framework to describe and model a design and proposed a DfAM system organized in several modules dealing with the modeling, manufacturing simulation, and design behavior analysis phases. Ponche et al. [26] presented a DfAM methodology that takes into account the design requirements and the manufacturing specificities, adopting a redesign strategy based on the functional surface approach; they concentrated on metallic components produced by Additive Laser Manufacturing. Vayre et al. [27] applied a four-step designing methodology consisting of initial shape generation, set of geometrical parameter definition, shape optimization through the tuning of the parameters, and final validation of a metallic part produced by direct metal deposition and electron beam melting AM technologies. Briard et al. [28] presented a four-step methodology to maximize the potential of generative design coupled with DfAM; the first phase deals with the translation of the problem to a suitable input for generative design, whereas the following three phases deal with an unconstrained iterative optimization, an iterative optimization driven by the AM guidelines, and a final iterative optimization refining the part including AM-enabled structures, such as lattices. Duro-Royo et al. [29] presented a computational workflow for the design and the fabrication of multi-material and multi-scale structured objects; they focused on water-based heterogeneous materials based on polysaccharide hydrogels in 1% to 12% concentrations in *w/v* of 1% acetic acid aqueous solutions and these gels were also mixed with cellulose microfiber to obtain volumetric composites. They created a model that considers the input data, like materials and geometry, and calculates all the instructions for the object fabrication via a pneumatic extruder mounted on a six-axes robotic arm. Boddeti et al. [30] presented a digital design and manufacturing workflow able to design both the macroscopic topology and the microstructure of an object; the workflow is divided into three steps: a design automation process that optimizes the material distribution and its microstructure, a material compilation process that creates a material layout and generates the code for fabrication, and a digital fabrication step with multi-material photopolymer material jetting technology. Zhang et al. [31] proposed an evaluation framework to assess the design from the perspective of process planning for AM; two sets of indicators were used to check whether the part is suitable to be produced by AM manufacturing and to verify the design's utilization of the characteristics of an AM process. Similarly, Lettori et al. [32] proposed an approach to assess the compatibility and suitability of a product for the AM production through a set of reference questions and a compliance index; then, they validated the method with case studies found in the literature. Motyl and Filippi [33] reviewed the scientific literature to explore the relationship between AM processes and product design, concentrating on the conceptual design phase and the theory of inventive problem solving (TRIZ) [34]; some of the analyzed works use the TRIZ for the definition of the DfAM guidelines.

Nonetheless, the literature highlights the lack of exhaustive frameworks that describe the design process and take full advantage of the possibilities offered by AM. Seepersad [35] stated that advances are still needed to couple computer-aided design (CAD) software and computer-aided engineering (CAE) tools to incorporate the DfAM knowledge into the design process. Kumke et al. [36] highlighted some limitations on the existing DfAM frameworks too: they do not cover the entire design process steps, they focus on the utilization of a single AM potential, and they are often too specific for a single case study.

In this contribution, a heuristic design workflow for AM is proposed aimed at exploiting the new possibilities offered by AM technologies and the high computational resources available nowadays. The workflow focuses on the product design phase, also referred to as embodiment design [20,37], where the design is developed up to the production. It specifically concentrates on cases in which mechanical performances are required, together with a reduction of the weight of the parts. Different geometric modeling opportunities and structural optimization techniques are presented: commercial software is used to perform the topology optimization and the redesign of the optimized results. As an alternative, a method developed by the research group designs conformal lattice structures with size optimization performed on the beams and allows to automatically obtain a smooth mesh model. The proposed workflow is then validated on a test case, adopting different design methods based on lattice structures, PolyNurbs, and parametric CAD to reach innovative solutions.

2. Design Workflow

The proposed workflow helps the designer during the product development process of AM components, guiding him throughout decisions that allow to fully exploit AM potential. AM-related engineering requirements and technological constraints are considered in the first phases of the workflow and simulation tools are used to optimize and validate the geometric model. In particular, the workflow can be adopted during the embodiment design phase of parts in which the mechanical performance needs to be maximized and the weight needs to be as low as possible. Structural optimization approaches such as size and topology optimization perfectly suit this scenario.

Figure 2 shows the proposed design workflow for AM. First, the design space is identified. The design space is a volume where the material distribution is going to be optimized; it can be obtained from an existing model or it can be specifically designed considering the maximum allowable size of the component. Then, two paths can be followed: the first one performs a topology optimization on the entire design space, whereas the second one performs a size optimization on a lattice structure. Regardless of the selected approach, a finite element (FE) model is created taking into consideration not only the "usual" boundary conditions such as the material, the loads, and the constraints but also the constraints and conditions strictly related to the design for AM. For instance, the technological constraints could include a limit for the inclination of the structure to avoid overhang angles (if required by the manufacturing technology) and the upper and lower limits for the most critical features, i.e., hole size, strut dimension, wall thickness, etc. Furthermore, since AM allows the production of complex geometrical shapes, it is easier to create parts resulting from multi-objective optimization; the optimization goals like targeted mass and natural frequencies, or desired heat exchanging properties can be considered as engineering requirements. Including this information in the first part of the workflow enables to obtain a design with the desired functionalities that is likely to be produced without the need of stepping back to the product development phase.

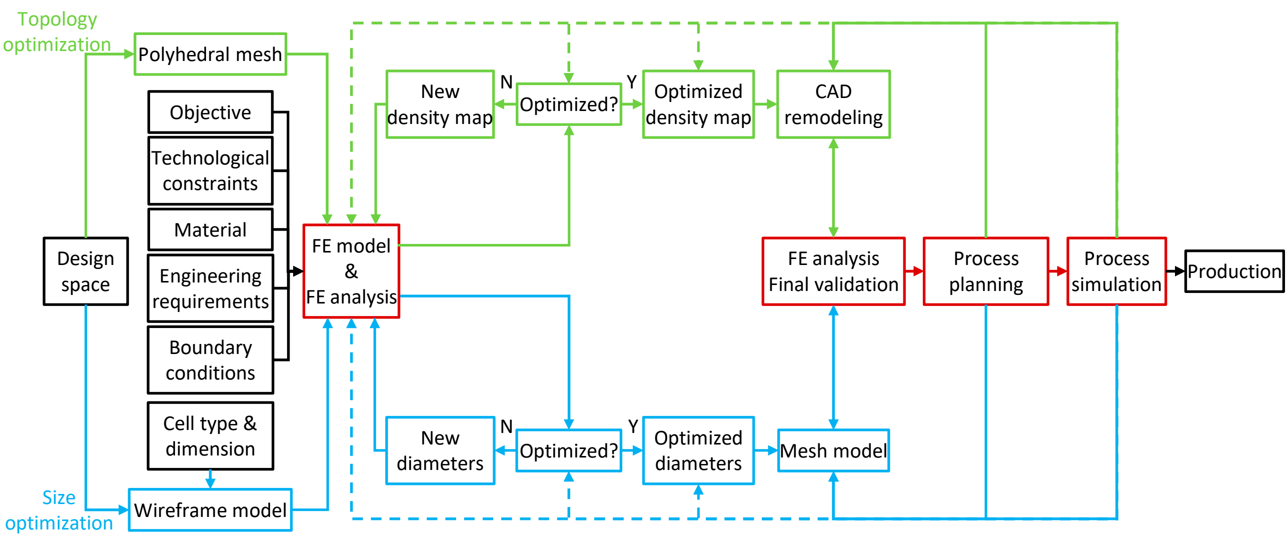

Figure 2. The proposed design workflow for additive manufacturing. Black blocks: steps related to the boundary conditions; green blocks: steps related to the topology optimization; blue blocks: steps related to the size optimization; red blocks: steps related to computer-aided engineering (CAE) simulation software.

If the topology optimization approach is chosen, the design space is discretized and a polyhedral mesh is obtained; then, the topology optimization is performed. During this process, the material is arranged inside the design space to find the best distribution of material under a set of boundary conditions and respecting the structural and dimensional performance requirements. According to the literature, several topology optimization algorithms can be used [38]. Homogenization methods use the mathematical theory of homogenization [39,40] to study a complex domain previously divided into microstructures, i.e., the finite elements, as a continuum domain made up of a virtual material called effective material [41]. Density methods consider the density as the only design variable for each finite element, and the variable can assume a value between 0 and 1; since the optimal solutions would consist of elements with values mostly between 0 and 1, the results would be far from a solid (1)–void (0) situation. The most popular numerical method for suppressing intermediate densities is the Solid Isotropic Microstructure with Penalization (SIMP) method, proposed by Bendsoe [42], which penalizes elements with intermediate densities exploiting a power law. To avoid intermediate densities in the optimized solution, discrete methods, also called "hard-kill" methods, can be used; in the Evolutionary Structural Optimization (ESO) method proposed by Xie and Steven [43], a criterion parameter is calculated for each element and at each iteration the elements with the lowest criterion parameter value are eliminated. Furthermore, Bi-directional Evolutionary Structural Optimization (BESO) method [44] is an extension of ESO, in which new elements can be added next to those elements with a high criterion parameter at each iteration. Level-set Methods (LSMs) are another category of topology optimization methods where the iso-contours of a level-set function implicitly define the interface between the material phases [45,46]; this approach allows to obtain a sharp transition between void and solid regions. In the proposed workflow, a SIMP density method is adopted because this method requires relatively few iterations, is suitable for a combination of a wide range of design constraints, multiple load conditions, multi-physics problems, and extremely large (often 3D) systems, is extensively used in industrial software [38], and can be easily implemented with a simple code [47,48]. As a result of the SIMP method, a density map is obtained, which is contoured to a specific level of density (threshold), obtaining a mesh surface. Often, the resulting mesh cannot be directly used for the production phase due to the lack of connection zones or the presence of coarse regions due to the process discretization. The remodeling of the topology optimization mesh is a research topic of interest, indeed. Zegard and Paulino [49] presented a tool that generates suitable outputs for AM by using filters and the continuation approach on the penalization parameter; Jiu et al. [50] proposed a CAD-oriented topology optimization method able to perform the optimization directly on the CAD model instead of on the mesh. Most of the time the procedure is operated manually, and the part is modeled in a CAD environment using the mesh as guideline during the modeling. Alternatively, software tools for automatic remodeling are available; these mainly adopt quad-remesh and subdivision surface approaches.

If the size optimization approach is followed, given a cell type and the unit cell dimension, a wireframe model is obtained filling the design space with a conformal lattice structure. In a conformal structure, the unit cell can deform to adapt to the boundary of the part or the lines of the stress field; this feature eliminates weakness at boundaries and provides stiffness and resistance to the entire model [51]. The size optimization is then performed on the wireframe [52,53]. The diameter of the beams iteratively varies until all the beams reach the target utilization, defined as the ratio between the maximum Von Mises stress measured on the beam and the admissible stress; as previously highlighted, the size of the beam is controlled to ensure that the beam diameter is thick enough to be manufactured and that it does not exceed the upper bound to avoid interferences with the surrounding beams. The optimized wireframe is then modeled with a boundary representation mesh-based approach as proposed by Savio et al. [54]. The obtained coarse mesh is then smoothed adopting the Catmull–Clark subdivision surface algorithm [55]: each quad face is subdivided into four smaller quad faces at every iteration. The algorithm produces a surface with continuity in curvature (C2 surface), except at extraordinary vertices where they are C1. This allows to reduce stress concentration, especially at nodal points, enhancing the mechanical properties and the fatigue life of the lattice [56–58].

Alternatively, it is possible to combine topology and size optimization. The literature shows how the density map of the topology optimization can be used to assign an optimized dimension to the diameter of a beam-like lattice structure [59,60] and to the thickness of a shell-like lattice structure [61].

Once the optimized part is modeled, it is necessary to perform an additional FE analysis to mechanically validate the final model. This step is mandatory in topology optimization because during the modeling phase weak zones could arise, especially if manual remodeling is adopted. After that, process-related considerations are done. Process planning deals with all the necessary operations needed once the AM production technology and machine have been selected. The orientation of the part inside the manufacturing machine, the generation of the supports (if needed), and the generation of the print path strategy affect the quality of the printed part, i.e., the surface texture and the mechanical properties [26], the material and energy consumption, and the production time [62–64]. Then, process simulation helps to predict residual stress and geometric distortion of the printed parts, avoiding time-consuming and expensive experimental campaigns based on trial and error. The evaluation of residual stresses and thermal distortions allows compensating the geometrical CAD model obtaining parts with the desired dimensional specifications and mechanical properties, reducing the probability of defects that lead to crack initiation, propagation, and failure both during the printing and the utilization of the product, especially when dealing with metallic components [65]. Process simulation methods that concentrate not only on metals AM techniques [66–69] but also on material extrusion [70,71] and powder bed fusion [72,73] of polymers can be found. If the FE analysis fails to validate the component or if the manufacturing process simulation highlights dimensional deformation and residual stresses higher than requirements, it is necessary to remodel the part or to step back to the optimization phase, changing the boundary conditions of the model.

When all these steps are successfully completed, the part is ready to be produced. The component is optimized for the intended use and it is likely to not encounter manufacturing issues during the printing phase. An important consideration is whether to use the topology optimization or the size optimization approach. One option could be to apply both and compare the solutions, choosing the one that best suits the application, but it is computationally demanding. Some a priori thoughts can help to decide as well. If the part is metallic, the struts of the lattice could act as internal supports, heat dissipators, and prevent thermal warping. Furthermore, being less bulky, the lattice structure could present lower residual stress. The mechanical validation of a lattice structure requires high computational resources and it is time consuming due to the high number of 3D elements needed to mesh the structure; at the same time, while the FE validation analysis is mandatory for the topology optimized part because the manual remodeling phase can introduce weak areas, it is less necessary for the lattice structure model because the diameters of the beams were previously optimized through a FE analysis and in the presented mesh modeling approach the optimized value is adopted at the middle of the beam, whereas the diameter tends to increase towards the nodal points.

3. Case Study

The proposed workflow was applied to the remodeling of a piston rod. Reducing the weight of a piston rod while maintaining the mechanical performance is an important goal, especially in competitions in the automotive fields, but also in the industry where weight reduction leads to less inertia and to a reduction of energy consumption.

The part is currently produced with a pressure die-casting process and is intended to be produced with the Selective Laser Melting (SLM) powder bed fusion AM technology. The material is an aluminum AlSi10Mg with properties as in Table 1.

Table 1. Aluminum AlSi10Mg properties.

Density	2700 kg/m^3
Young modulus	68 GPa
Yield strength	190 MPa
Ultimate tensile strength	335 MPa
Poisson Ratio	0.30

Overall dimensions, loads, and constraints applied to the piston rod are shown in Figure 3a,b, respectively. The loads and constraints are summarized in Table 2.

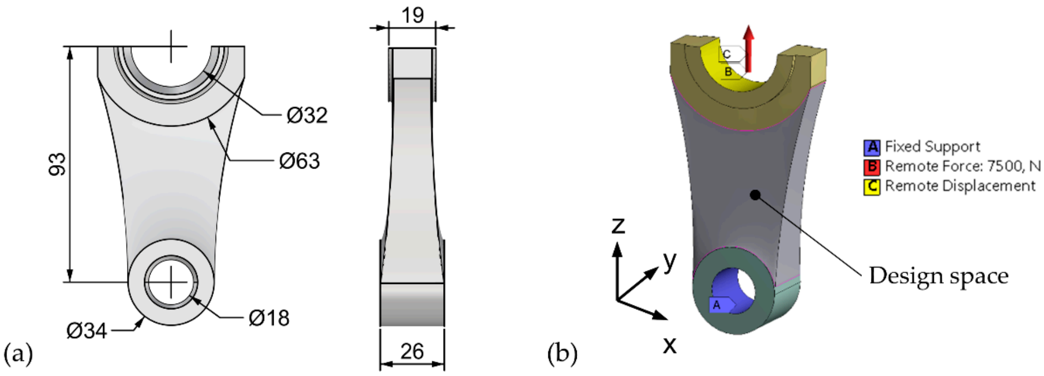

Figure 3. Piston rod: (**a**) overall dimension, (**b**) boundary conditions and design space.

Table 2. Load and constraints applied to the piston rod.

Load	7.5 kN axial traction along z-axis. Applies to big rod's end face.
Constraints	All the displacements and rotations locked. Applies to inner face of the small rod's end. Displacements along x- and y-directions locked. Applies to big rod's end face.

The topology optimization of the design space was performed in SolidWorks 2019 (Dassault Systèmes) using the SolidWorks Simulation module; the software adopts the SIMP method for solving the optimization problem. The "best stiffness to weight ratio" goals was set, using the constraint of a final mass equal to 25% of the original part. The symmetry of the final part with respect to the YZ and ZX plane was imposed. Figure 4a shows the mesh resulting from the topology optimization. This mesh was then used as a starting point for the manual remodeling phase, performed in Inspire Studio CAD 3D software (Altair), as in Figure 4b.

The size optimization section of the workflow was performed in Rhinoceros 6 (Robert McNeel & Associates) inside Grasshopper environment. The design space was filled with a conformal wireframe based on the simple cubic unit cell; the number of instances is 10, 4, and 15 along the x-, y-, and z-axis, respectively, and the minimum element size equals 3 mm. The FE beams model was set-up using Karamba3D plugin [74]. The loads and the constraints were directly applied at the nodes of the beams placed at the interface between the design space and the big and small rod's ends; the 7.5 kN load was equally distributed on each node of the upper part of the wireframe, so as the rotation and translation constraints on each node of the lower and upper part of the wireframe. The target utilization ratio was set to (90 $\pm$ 1)% with respect to the yield strength. The upper and lower bound for the diameter of the beams were defined as 1.5 mm and 0.5 mm, respectively. Figure 5 shows the conformal wireframe and the utilization ratio of the optimized structure. Some beams do not reach the required utilization ratio; indeed, they present a utilization ratio lower than the target because the optimized diameter was smaller than the minimum allowable size (i.e., 0.5 mm), so, being assigned the 0.5 mm diameter, they are under-utilized.

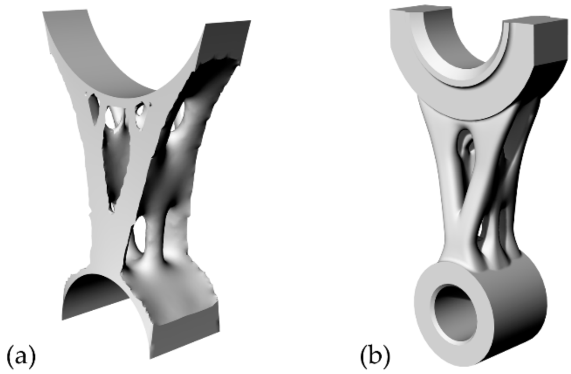

Figure 4. Topology optimization: (**a**) SolidWorks Simulation result (mesh), (**b**) Inspire Studio manual remodeling result (NURBS).

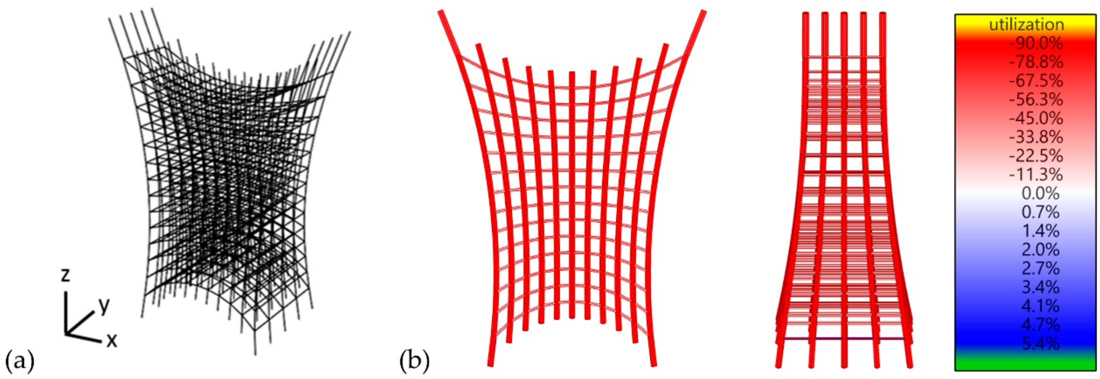

Figure 5. Size optimization: (**a**) wireframe model, (**b**) utilization ratio of the optimized structure (compression is positive).

The lattice structure was then modeled adopting the mesh approach and the Catmull–Clark subdivision surface algorithm. As can be seen in Figure 6, smooth surfaces are obtained, especially at nodal points.

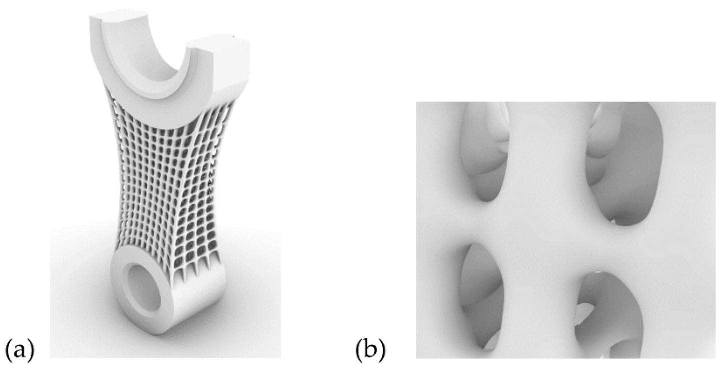

Figure 6. Modeled lattice structure: (**a**) lattice connected to the piston rod's ends, (**b**) detail on the smooth surfaces at nodal points.

Then, the two models obtained from the topology and the size optimization were validated through FE analyses in Ansys Mechanical 2019 R1. The parts were meshed with tetrahedron elements using an element minimum size of 0.1 mm and an element maximum size of 1 mm. The meshing method is patch-independent and includes automatic refinement in curvature and proximity. The symmetry of the topology optimized part with respect to the ZX and YZ plane was exploited to simulate only one quarter of the model. The results are represented in Figure 7. In the size optimized model (Figure 7b), the higher value of stress observed on the legend is related to the absence of fillet between the lattice structure and the body and does not depend on the modeling method of the lattice.

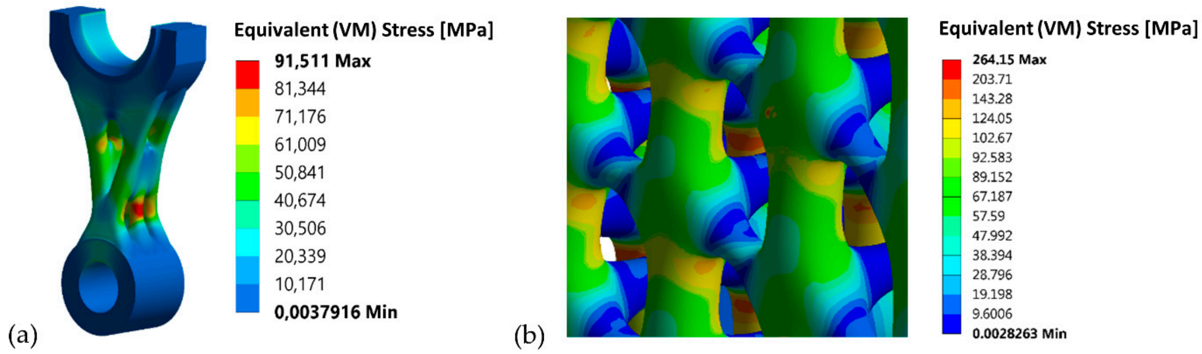

Figure 7. FE analyses validation, equivalent Von Mises stress: (**a**) topology optimization, (**b**) size optimization.

Netfabb Premium 2020.3 (Autodesk) was used for preliminary process planning, choosing for the best part orientation. Supports too were created inside the software. The Renishaw AM 400 SLM machine was selected, together with the default material configuration for Aluminum AlSi10Mg-0403 printed with a 25 μm layer thickness, as suggested by the powders manufacturer [75]. First, the topology optimized model was oriented. Among the proposed orientations, three are reported in Figure 8. The final decision is driven by several considerations. The orientation in Figure 8a has the lowest height, resulting in faster printing time, but presents the highest supported area, requiring more time for supports removal and post-process such as sandblasting to avoid the lower quality of the surface finish in the supported areas; the configuration in Figure 8b has the less supported area, but has the highest support volume and height, resulting in a long build time and high material waste; the configuration in Figure 8c has the lower support volume and a relatively low supported area and build time. Moreover, since the configuration in Figure 8a lays on the platform, the circular functional surfaces on the rod's ends will have the best dimensional and geometrical accuracy. Further milling operations could be needed to comply with the requested tolerances.

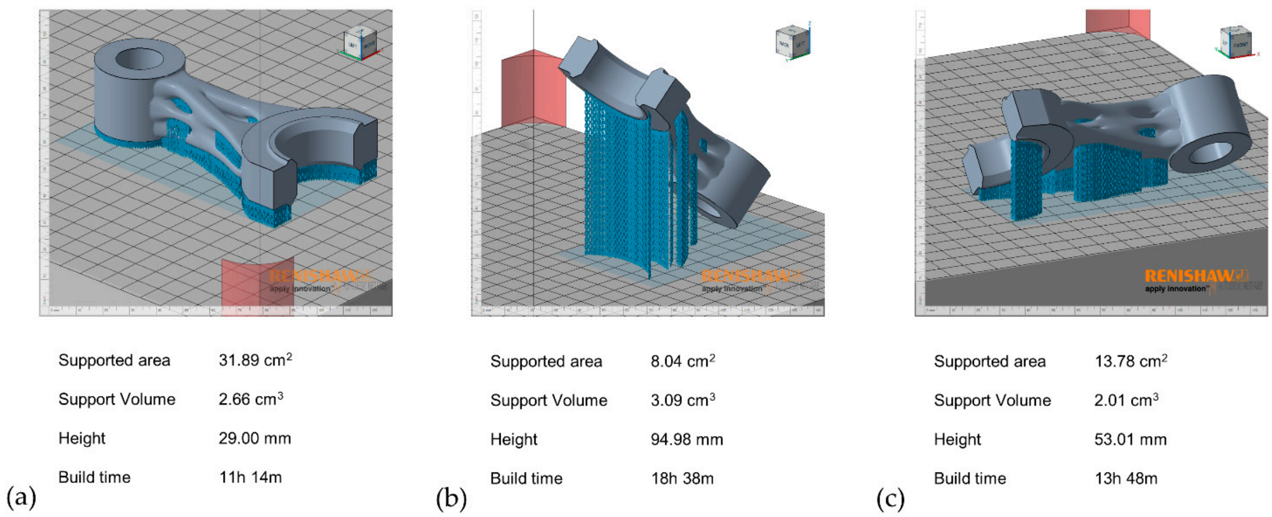

Figure 8. Part orientation and support generation for the topologically optimized piston rod. (**a**–**c**) show three possible orientations.

The same procedure was followed for the orientation of the piston rod with the lattice structure. This time, due to the extreme difficulty of removing the supports between the beams of the lattice, the only orientation that did not present supports in the central part of the model was chosen, as shown in Figure 9.

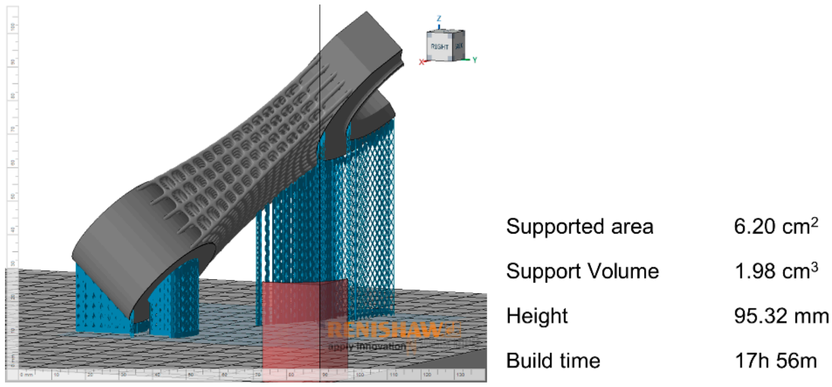

Figure 9. Part orientation and support generation for the size optimized piston rod.

Finally, the next step would be to perform the process simulation of the oriented part to assess the printability of the models, the geometrical distortions, and the residual stresses. According to the results, the designer can consider geometrically compensating the part, changing the part orientation, or going back to the modeling phase and remodel the part.

The application of the workflow for redesigning the piston rod enabled to obtain two optimized parts and a considerable reduction of the mass, as shown in Table 3. The two methods present some drawbacks too. The topology optimized model requires manual remodeling, and it is more prone to failure during the final FE analysis verification, due to human errors during the remodeling phase. The proposed method for the size optimization is in its prototypal stage and it still has a limited choice of unit cells and does not correctly manage the connection between the lattice structure and the adjacent objects. Numerical analyses on the lattice model are computationally demanding but less necessary since the wireframe was previously optimized and the mesh modeling method does not alter the diameter of the beams.

Table 3. Mass reduction of the optimized models. The mass only considers the design space volume and not the rod's ends, which were not optimized.

Model/Approach	Mass [g]	% of Mass Reduction
Starting design space	104.7	
Topology optimization	29.99	−71%
Size optimization	20.98	−80%

4. Conclusions

In this work, a design workflow for Additive Manufacturing was proposed, trying to overcome the limits highlighted in the literature, where it is stated that the available frameworks do not exploit all the advantages offered by AM and do not cover the entire design process. The presented workflow considers the embodiment design phase, from the definition of a design volume to the production of the part, integrating both CAD tools for the geometric modeling of the part and CAE tools for the optimization and simulation phases; more, it considers the possibility to use the size optimization to obtain lattice structures with optimized beams, and the topology optimization to obtain more organic shapes. The workflow was then applied to the remodeling and optimization of a piston rod in which both commercial and custom tools were adopted, showing its ease and universality of implementation.

As future works, the process simulation will be performed on the oriented parts. Then, a hybrid method that combines size and topology optimization is going to be developed to further expand the workflow possibilities; the 0–1 density parameter will drive the dimension of the beams, shell, or solid elements. The connection between the lattice structures and the adjacent objects will be addressed to obtain smoother links and enhance the mechanical properties of the parts. Moreover, aspects related to hybrid manufacturing technologies will be addressed.

Author Contributions: Conceptualization, S.R., F.U., L.G., G.S., R.M., and G.C.; Formal analysis, S.R., F.U., and L.G.; Funding acquisition, G.S., R.M., and G.C.; Investigation, S.R.; Methodology, S.R., and G.S.; Supervision, G.S., R.M., and G.C.; Writing—original draft, S.R.; Writing—review and editing, S.R., F.U., L.G., G.S., R.M., and G.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by a Ph.D. grant of Fondazione Cassa di Risparmio di Padova e Rovigo (CARIPARO), by the grant "FSE 2105-37-11-2018: Hybrid manufacturing strategies through selective laser sintering for the customization of series components" by Regione Veneto, and by the grant "BIRD 190850—Design, geometric modeling and analysis of components with functionally graded variation for additive manufacturing technologies" by the Department of Civil, Environmental, and Architectural Engineering, University of Padova, Italy.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The raw/processed data required to reproduce these findings can be partially shared upon request.

Conflicts of Interest: The authors declare no conflict of interest.

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