engineering proceedings

MDPI

Proceeding Paper

Topological Optimization for the Redesigning of Components in Additive Manufacturing: The Case Study of the Connecting Rod †

Michele Trovato *, Federico Perquoti and Paolo Cicconi

Department of Industrial, Electronic and Mechanical Engineering, Università degli Studi ROMA TRE, 00146 Rome, Italy; paolo.cicconi@uniroma3.it (P.C.)

* Correspondence: michele.trovato@uniroma3.it

† Presented at the 4th International Electronic Conference on Applied Sciences, Online, 27 October–10 November 2023.

Abstract: Additive manufacturing allows the creation of geometries otherwise impossible to achieve through traditional technologies in mechanical components. These geometries can be obtained using algorithms to optimize the mass distribution. Topology Optimization algorithms are one of the tools most applied in design for additive manufacturing and lightweight engineering. These optimization techniques require Finite Element Method tools to evaluate and compare the mechanical behavior of different geometrical solutions. The optimization results are closely related to boundary conditions, objectives, and constraints. Therefore, one of the issues is the necessity to evaluate different parameter settings to improve the result in terms of light weight, strength, and easy printability. This article shows a working method for using topological optimization to lighten a connecting rod. The resultant model is optimized considering Additive Manufacturing.

Keywords: design for additive manufacturing; topological optimization; additive manufacturing; lightweight engineering; connecting rod

check for updates

Citation: Trovato, M.; Perquoti, F.; Cicconi, P. Topological Optimization for the Redesigning of Components in Additive Manufacturing: The Case Study of the Connecting Rod. *Eng. Proc.* **2023**, *56*, 131. https://doi.org/10.3390/ASEC2023-16638

Academic Editor: Marco Mandolini

Published: 19 December 2023

1. Introduction

Metal Additive Manufacturing (AM) enables the creation of components with geometric shapes that are impossible to achieve using traditional subtractive manufacturing techniques. The shapes can be modeled by lattice structures, which involve the spatial repetition of a unit cell with selected mechanical characteristics [1], or geometrical optimization methods based on mathematical algorithms. These methods are Generative Design, Topological Optimization (TO), Shape Optimization, and others [2]. The lightening of the parts, while maintaining the same mechanical properties and functionalities of the starting component, is the main purpose of these geometrical methods. One of the most frequently used methods to lighten components and obtain free-form geometries is the Topological Optimization (TO), where the material distribution is optimized by minimizing an objective function following different strategies such as the Solid Isotropic Material with Penalization (SIMP) method and Level Set Method [3]. On the other hand, the realization of shapes obtained using TO algorithms and similar methods requires an AM approach. Laser Powder Bed Fusion (L-PDF), also known as Selective Laser Melting (SLM), is the 3D metal printing process that allows high-level mechanical characteristics such as low porosity, surface finishing, and geometrical accuracy to be achieved [4].

This paper aims to identify a method for lightweight components using topological optimization to be realized using the L-PBF process, combining geometric optimizations with the known constraints of metallic AM. As a test case, this paper optimizes a connecting rod, considering weight reduction and printability. The document describes the research background in Section 2, the proposed method in Section 3, and the case study in Section 4. Finally, Section 5 ends with conclusions.

2. Research Background

2.1. Topology Optimization

TO is one of the most frequently used methods to optimize the material distribution in structural components. It is based on the iterative removal of unnecessary material within a predefined initial volume, known as a Design Space, by a given configuration of loads, constraints, optimization objectives, and functional regions to be preserved in a Non-Design Space. The material distribution problem has been introduced by Bendsøe, defining the process of shape optimization as research into the best way to arrange spatial material distribution on specific loads and boundary conditions [5].

Generally, the objective of the TO problem is to minimize compliance, which essentially means maximizing the overall stiffness of the structure. This optimization approach is valuable in engineering, enabling weight reduction while maintaining its stiffness-related characteristics intact.

The most widespread and frequently used topological optimization methods are the Solid Isotropic Material Method (SIMP) and the Level Set Method (LSM). Both are based on the Finite Element Method (FEM) discretization mesh, where the Design Space is analyzed with a Finite Element Analysis (FEA) that determines the displacement and stress gradients that help TO in the selection of elements that are not useful for the optimization problem.

The SIMP method, also called the "density method", is based on the relation between the density design variable and the material property of each element of the mesh, bound by the penalization parameter. The penalization effect only works in the presence of a volume constraint or some other constraint that indirectly limits volume [6]. On the other hand, the SLM method is based on employing a continuous level-set function, where the interface is associated with the contour where the function equals zero. In practice, this level-set function is a Lipschitz continuous real-valued function. It serves as a scalar field that represents the distance to the nearest interface or boundary. The boundary of the design is implicitly represented as the zero-level set of the function [7].

2.2. Additive Manufacturing

AM is defined according to the ISO/ASTM 52900:2022 standard [8] as the method of building components from 3D CAD models by incrementally adding material, typically layer by layer. This approach contrasts traditional techniques like subtractive and formative manufacturing. AM has evolved into a relevant method of producing parts, particularly due to its capacity to fabricate complex shapes that are impossible to produce with other technologies. Seven distinctive categories of AM processes have been identified for generating objects based on 3D CAD models. The materials employed in these procedures are plastics, composites, ceramics, and diverse metal alloys like steel, aluminum, titanium-aluminum, copper, and more.

Laser Powder Bed Fusion (L-PBF), also known as Selective Laser Melting (SLM), is the technique that delivers optimal results in achieving precise surface smoothness and tolerances for the manufacture of metallic components. L-PBF is based on fusing thin layers of metal powder, known as "layers", using thermal energy generated by a laser source [9]. During this procedure, the laser beam fully melts the metal powder particles due to the high energy input. The L-PBF method facilitates the creation of components with a density nearly equivalent to those obtained through traditional foundry processes. To achieve high density, the metal powder particles are entirely melted, generating residual stresses due to significant thermal gradients between the layers. However, these stresses could potentially lead to issues such as distortion, delamination, or cracking, which might result in part failure [10].

The results of the L-PBF process can be affected by numerous drawbacks. Some geometrical drawbacks include the minimum wall thickness and hole clearance. Others are related to the printed parts' final quality, such as the dimensional accuracy, porosity, or surface roughness. Drawbacks related to the process concern support structures, the building time, the cost of process and materials, and the necessity of cutting and removing the base and supports [11]. The support structures are necessary to print metal parts with surfaces with critical overhang angles. Moreover, these supports contribute to heat dissipation, reducing the risk of deformation and residual stress due to the high thermal gradients. However, the supports must be easily removable and lightweight to reduce the scraps [12]. Another factor to be considered in metal printing is the part orientation, which affects the quantity and the extension of the overhang surfaces. The orientation should consider the best trade-off between production time, cost, removability, and accuracy [13].

Printing simulation tools can be used to avoid material waste and failures. Thus, these tools can reduce costs and printing time due to design errors. Choosing the correct process parameters makes it possible to predict if the printing process will be successful [14]. If this happens, the component is ready to be printed; otherwise, it is necessary to go back and modify the project.

2.3. Connecting Rod

The main mechanism that allows Internal Combustion Engines (ICE) to work is the connecting rod–crank–piston system. This mechanism transforms the translational motion generated by combustion inside the cylinder into rotary motion (Figure 1).

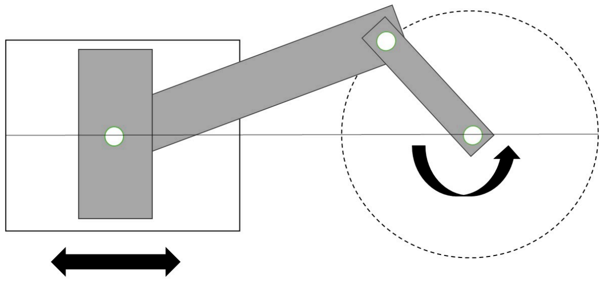


Figure 1. Piston-connecting rod–crank system.

Inertial forces play a fundamental role in the balance of forces and engine efficiency. By making these key parts lighter, it is possible to improve the overall performance of the ICE [15]. This paper focuses on the optimization and lightening of a connecting rod.

The connecting rod is an intermediary component connecting the piston and the crankshaft. Its main role involves transferring the push-pull action from the piston pin to the crankpin, converting the piston's reciprocating linear movement into the rotary motion of the crankshaft. This conventional design of the connecting rod is commonly observed within an ICE [16].

The connecting rod is constantly subjected to alternating tension and compression stresses which vary in magnitude and direction during its operation. When the dimensions of the connecting rod are too large, it not only leads to the wastage of materials but also compromises the equilibrium of system motion, resulting in excessive noise during operation. As a result, the effectiveness and dependability of the connecting rod structure directly impact the smooth functioning of the ICE [17].

3. Method

Figure 2 shows the workflow used in this work. This method aims to integrate the phases of Topology Optimization and AM simulation with a knowledge base that supports the study of the lightweight design without compromising the printability of the part. The method can be divided into three major phases. The first one concerns the study of the starting model, which is the component to be redesigned and optimized. The second phase is focused on the TO of the mechanical part. The third one is the redesigning of the component considering the known constraints of the AM process.

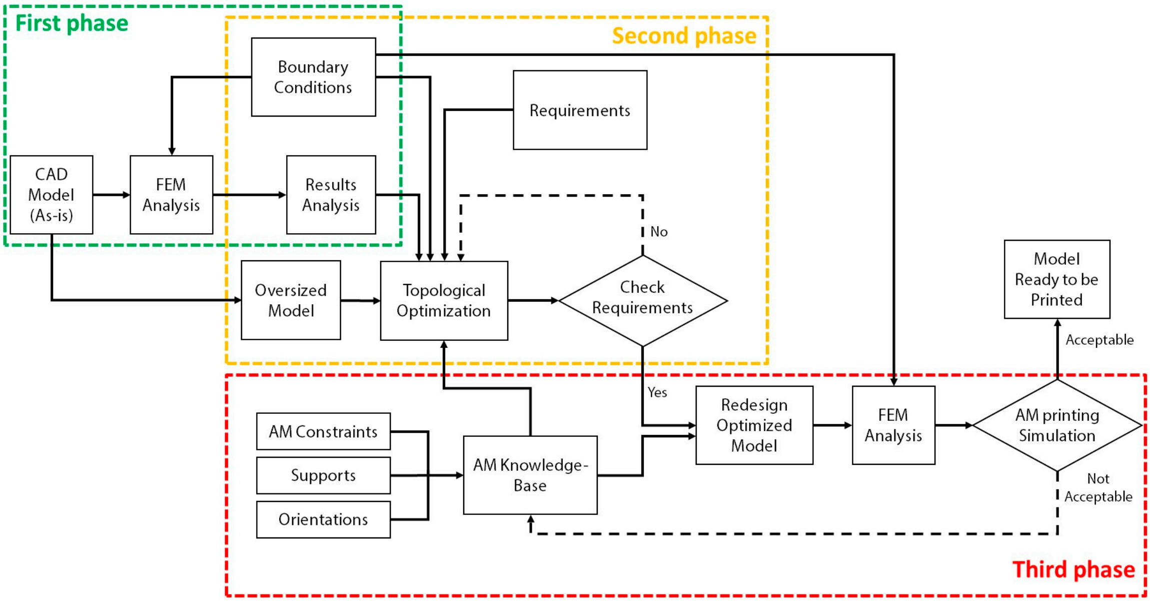
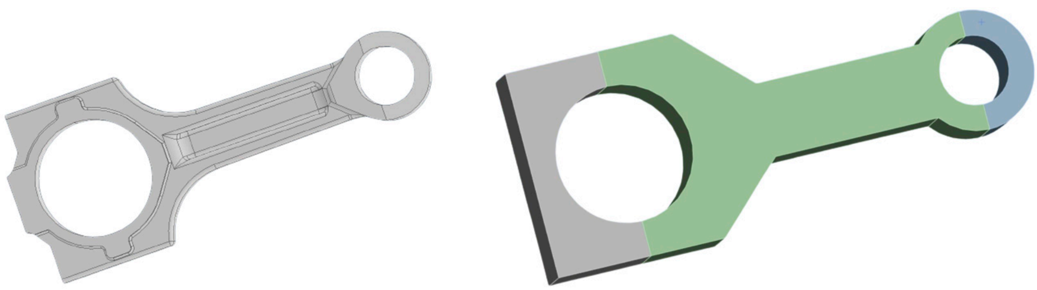


Figure 2. Proposed method to optimize the redesign of additive components.

The first phase begins with CAD modeling (as-is model). This can be obtained through different techniques, such as reverse engineering. The original CAD model is imported into a Finite Element Method (FEM) system to study its mechanical behavior under the boundary conditions.

The second phase concerns the optimization of the geometry using the TO approach with an oversized CAD model as input. The oversized CAD model (Figure 3b) is used to limit the influence of the input model on the TO computation. The boundary conditions must be the same as the previous FEM analysis.



(**a**) (**b**)

Figure 3. (**a**) CAD model (as-is); (**b**) oversized CAD model used for the TO analysis.

To correctly apply the TO method, it is necessary to carefully choose objective functions and constraints, such as mass reduction and symmetries. Each configuration affects the result of the TO calculation. The objective functions and constraints can be seen as parameters of the overall optimization process. The selection of objectives and constraints should be oriented to obtain a printable geometry, avoiding bodies with internal cavities, thin walls, and holes with critical diameters. This iterative phase can be repetitive and long. However, the introduction of a knowledge base can bridge the gap between the TO analysis and the AM process.

The third phase regards the final CAD modeling, starting from the resulting geometry of the TO analysis. The objective is to arrive at a component that can be 3D printed. Therefore, it is necessary to consider the AM process constraints and evaluate the best tradeoff between orientation and support structures. During this phase, the optimized model is redesigned, considering all these factors. The FEM analysis is applied with the same boundary conditions to validate the final model. Finally, the AM printing simulation is applied to evaluate stress and deformation during and after manufacturing. If the result is acceptable, the part is ready to be printed; otherwise, something must be changed.

4. Case Study: Connecting Rod

The proposed method has been applied to optimize the connecting rod of a 1.6 L automotive diesel ICE, reducing the final weight and considering manufacturing with the AM process. CAD software (Autodesk® Inventor® 2024) was used for the geometrical model of the connecting rod, and two different FEM tools were used for the structural simulations and the 3D printing analysis.

4.1. CAD Models

The starting CAD model (as-is) was realized by reproducing the geometry of the real component (Figure 3a). An oversized CAD model (Figure 3b) was used as input geometry for the TO phase, considering a greater volume to not affect the optimization result. The oversized model considers the limited operative dimensions of the analyzed piston-connecting rod–crank system. This procedure allows the TO algorithm to be free as much as possible to remove material where it is not necessary.

4.2. Boundary Conditions, FEM (As-Is)

The loads acting on a connecting rod vary over time in direction and intensity. During the entire cycle, the connecting rod receives various tensile and compressive stresses. Five loading conditions (Table 1) were applied to the model to validate the component. To calculate the maximum compressive force, applied at the small end and the large one, a pressure of about 50 bar was considered in the combustion chamber at the top in the dead center.

Table 1. Load cases analyzed in the proposed study.

ID	Case	Applied Loads
1	Compression force at small end	$F_{max} = 25,000$ N
2	Tensile force at small end	$F_t = 8842$ N
3	Compression force at large end	$F_{max} = 25,000$ N
4	Tensile force at large end	$F_t = 8842$ N
5	Inertia bending	$F_r = 8000$ N; $M_{max} = 52.1$ Nm

On the other hand, the maximum tensile force was calculated considering the geometry of the piston-connecting rod–crank system and the maximum angular velocity. The tensile force was applied to the small and the large ends.

A fifth load condition considers the case of inertia bending. This case condition is verified when the angle between the connecting rod and the crank is 90°. In this load case, the bending moment due to inertia forces is about 52.1 Nm (M_{max}) and it is combined with a residual compression force of $F_r = 8000$ N, directed along the center of the crank rotation.

Figure 4 shows the stress distribution for load case ID 4, evaluated with FEM tools. This is the worst-case scenario between the five load cases considering the maximum von Mises stress. The most stressed area is the small end. Table 2 shows the results of the FEM analysis for each load case.

Table 2. Results of FEM Analysis.

Load ID	Equivalent von Mises Stress [MPa]	Displacement [mm]
1	165.8	0.045
2	177.1	0.049
3	175.9	0.061
4	200.1	0.062
5	41.6	0.006

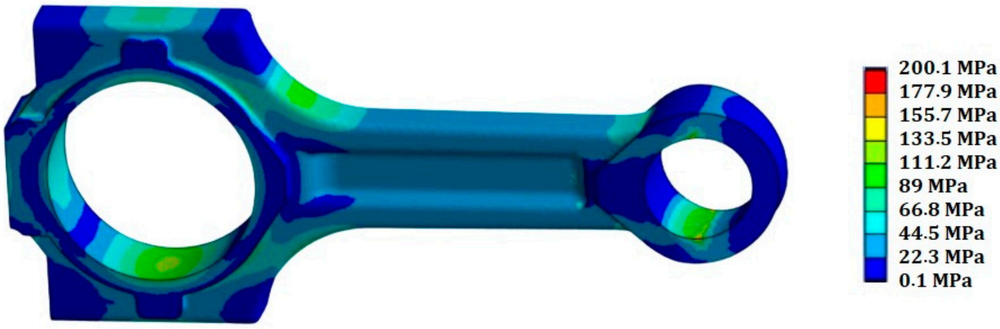


Figure 4. Stress distribution report for the ID 4 case (worst-case scenario).

Moreover, a modal analysis was performed to check the first natural frequency of the connecting rod. The first six modes of vibration are shown in Table 3.

Table 3. Modes of vibration.

Mode	1	2	3	4	5	6
Frequency [Hz]	648.74	1555.1	2409.1	4116.4	6415.5	9116.8

4.3. TO: Objectives, Constraints, Results

The SIMP method was used for the TO analysis. The optimization begins by defining the design and non-design zones, which are the areas where the algorithm can act or not act due to coupling with other parts of the assembly. The selection of the design and non-design zones is extremely relevant for the success of the optimization in terms of the 3D printability of the component. This analysis also requires boundary conditions, optimization constraints, and optimization objectives. To achieve a lightweight and printable component, a Ti-6AL-4V titanium alloy was chosen. The same loads applied to the FEM (as-is) analysis have been used. The chosen objective function is the minimization of the global compliance of the component due to all loads. The constraints chosen can be divided into two classes, and the first one concerns design constraints such as the symmetries of the connecting rod. The second includes the functional constraints related to stress and mass. The maximum stress was limited to 500 MPa, and the percentage of the final mass was between 15% and 20% of the input mode (oversized model). Figure 5 shows the result of the TO process after 56 iterations.

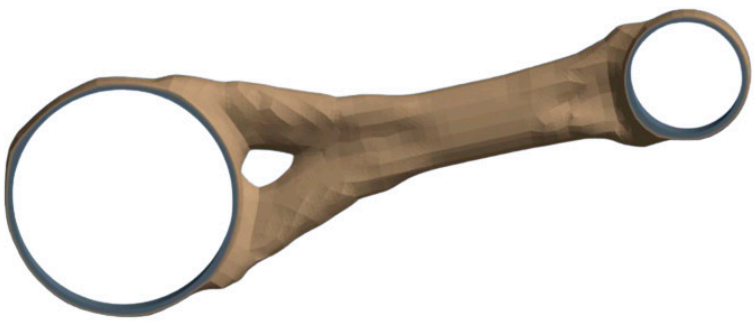
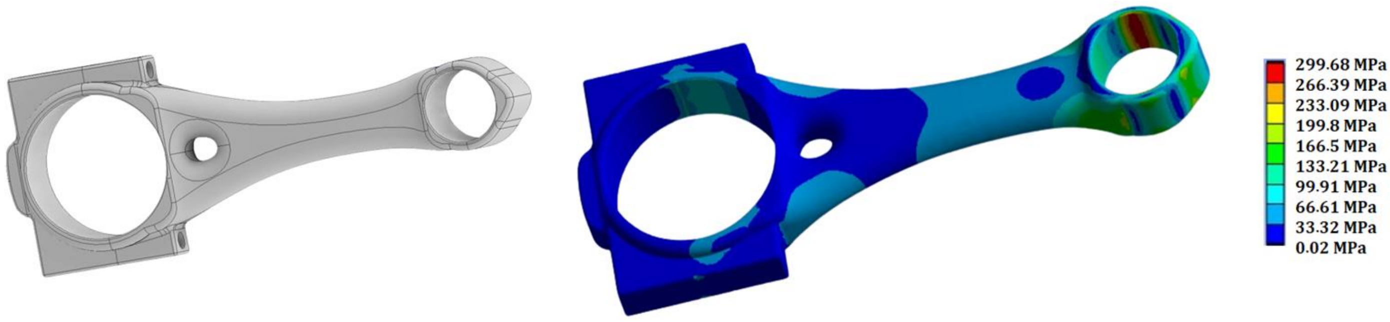


Figure 5. Result of the TO.

4.4. Redesign and Printing Simulation

Following the proposed method to realize a lightweight component that can be easily printed, it is necessary to consider the AM knowledge base during the redesign phase. Considering all the AM parameters and constraints, and the geometry obtained from the TO analysis, it is now possible to obtain a lighter component. Figure 6a reports the result of the final redesign phase.



(**a**) (**b**)

Figure 6. (**a**) Result of the redesign phase; (**b**) stress distribution—FEM analysis of the worst case (load case 2).

To validate this, optimized geometry is necessary to perform the FEM analysis again. The previous boundary conditions were used, and the result of the worst load case (load case 2) is shown in Figure 6b. Table 4 shows the results of the FEM analysis for each single load case. Table 5 shows the modes of vibration of the new part.

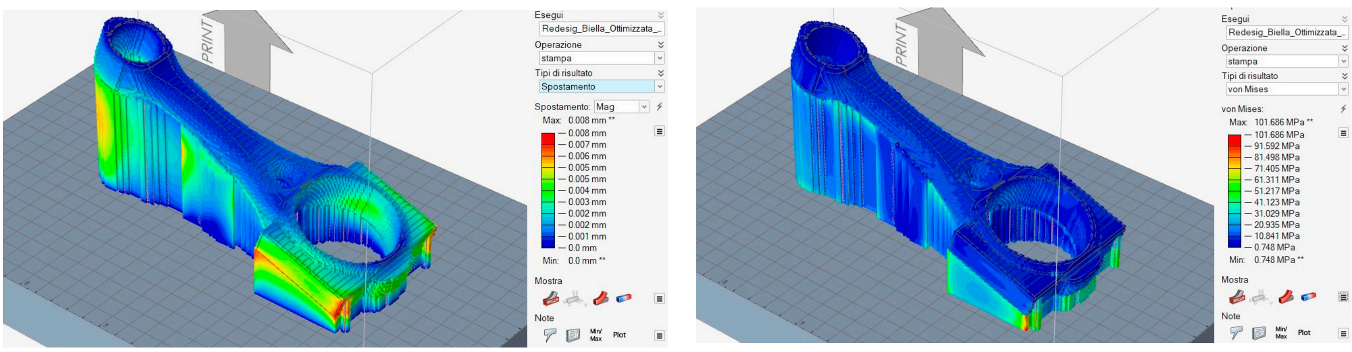
Table 4. Results of FEM analysis of the optimized geometry.

Load ID	Equivalent von Mises Stress [MPa]
1	156.2
2	299.7
3	111.5
4	239.5
5	39.8

Table 5. Modes of vibration of the optimized geometry.

Mode	1	2	3	4	5	6
Frequency [Hz]	744.72	1421.2	3930.1	4305.4	5400.9	8878.6

Figure 7 shows the results of the 3D printing simulation, reporting displacement (Figure 7a) and stress distribution (Figure 7b). The values of stress and deformation on the part can be considered acceptable. The connecting rod is now ready to be printed.



(**a**) (**b**)

Figure 7. (**a**) Displacement and (**b**) von Mises stress trends obtained with the printing simulation of the optimized connecting rod.

Table 6 shows how much the optimization of the geometry and the change of the material affects the final weight of the component. The TO process and the use of a performing titanium alloy (Ti-6AL-4V) reduce the volume by 21.8% and the overall weight of the connecting rod by 56.1%.

Table 6. Volume and weight comparison.

Model	Volumn [mm^3]	Weight [kg]
As-is	85,370	0.670
Redesigned	66,775	0.294

5. Conclusions

To summarize, this paper proposes a method to redesign a lightweight mechanical part with AM. The main purpose of this article is to analyze an approach that can integrate geometric optimization methods with the AM knowledge base. The method starts with the CAD modeling of a real component and uses tools such as FEM, TO, and the AM knowledge base to optimize the part. The AM knowledge base includes the AM constraints and the choice of orientation and supports. The method also includes a 3D printing simulation to evaluate the behavior of the process and results. The overall approach shows the possibility of optimizing an additive component using tools to reduce weight, design time, and process time in manufacturing. A final AM simulation activity allows failures and defects to be reduced. By integrating different design tools and introducing a knowledge base, it is possible to reduce the lead time in the early design phases. The increased use of simulations in AM can reduce the cost of prototypes. Moreover, the use of knowledge base rules in design can avoid the need for analyzing feasible solutions.

Author Contributions: Conceptualization, M.T. and P.C.; methodology, M.T. and P.C.; software, M.T. and F.P.; validation, M.T., F.P. and P.C.; investigation, M.T. and F.P.; data curation, M.T. and P.C.; writing—original draft preparation, M.T.; writing—review and editing, P.C.; supervision, P.C. All authors have read and agreed to the published version of the manuscript.

Funding: Project ECS 0000024 Rome Technopole, Concession Decree No. 1051 of 23 June 2022 adopted by the Italian Ministry of University and Research, CUP B83C22002820006, Rome Technopole.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

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

References

1. Hanks, B.; Berthel, J.; Frecker, M.; Simpson, T.W. Mechanical properties of additively manufactured metal lattice structures: Data review and design interface. *Addit. Manuf.* **2020**, *35*, 101301. [CrossRef]
2. Vlah, D.; Žavbi, R.; Vukašinović, N. Evaluation of topology optimization and generative design tools as support for conceptual design. In Proceedings of the Design Society: DESIGN Conference, Online, 26–29 October 2020; Volume 1, pp. 451–460.
3. Rozvany, G.I.N. A critical review of established methods of structural topology optimization. *Struct. Multidisc. Optim.* **2009**, *37*, 217–237. [CrossRef]
4. Singh, D.D.; Mahender, T.; Reddy, A.R. Powder bed fusion process: A brief review. *Mater. Today Proc.* **2021**, *46*, 350–355. [CrossRef]
5. Bendsoe, M.P.; Sigmund, O. *Topology Optimization: Theory, Methods, and Applications*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2003.
6. Sigmund, O.; Maute, K. Topology optimization approaches. *Struct. Multidisc. Optim.* **2013**, *48*, 1031–1055. [CrossRef]
7. Ye, Q.; Guo, Y.; Chen, S.; Lei, N.; Gu, X.D. Topology optimization of conformal structures on manifolds using extended level set methods (X-LSM) and conformal geometry theory. *Comput. Methods Appl. Mech. Eng.* **2019**, *344*, 164–185. [CrossRef]
8. *Standard ISO/ASTM 52900:2022*; Additive Manufacturing—General Principles—Fundamentals and Vocabulary. International Organization for Standardization: Geneva, Switzerland, 2022.
9. Zitelli, C.; Folgarait, P.; Di Schino, A. Laser Powder Bed Fusion of Stainless Steel Grades: A Review. *Metals* **2019**, *9*, 731. [CrossRef]
10. Salmi, A.; Piscopo, G.; Atzeni, E.; Minetola, P.; Iuliano, L. On the Effect of Part Orientation on Stress Distribution in AlSi10Mg Specimens Fabricated by Laser Powder Bed Fusion (L-PBF). *Procedia CIRP* **2018**, *67*, 191–196. [CrossRef]

11. Trovato, M.; Cicconi, P. Design tools for metal additive manufacturing: A critical and perspective overview. *Procedia CIRP* **2023**, *119*, 1084–1090. [CrossRef]
12. Jiang, J.; Xu, X.; Stringer, J. Support Structures for Additive Manufacturing: A Review. *J. Manuf. Mater. Process.* **2018**, *2*, 64. [CrossRef]
13. Cheng, L.; To, A. Part-scale build orientation optimization for minimizing residual stress and support volume for metal additive manufacturing: Theory and experimental validation. *Comput.-Aided Des.* **2019**, *113*, 1–23. [CrossRef]
14. Ninpetch, P.; Kowitwarangkul, P.; Mahathanabodee, S.; Chalermkarnnon, P.; Ratanadecho, P. A review of computer simulations of metal 3D printing. *AIP Conf. Proc.* **2020**, *2279*, 050002.
15. Ibhadode, O. Structural Design Strategies for the Production of Internal Combustion Engine Components by Additive Manufacturing: A Case Study of a Connecting Rod. In *Renewable Energy—Recent Advances*; IntechOpen: London, UK, 2023.
16. Gopal, G.; Kumar, L.S.; Reddy, K.V.B.; Rao, M.U.M.M.; Srinivasulu, G. Analysis of Piston, Connecting rod and Crank shaft assembly. *Mater. Today Proc.* **2017**, *4*, 7810–7819. [CrossRef]
17. Cecchel, S.; Razavi, N.; Mega, F.; Cornacchia, G.; Avanzini, A.; Battini, D.; Berto, F. Fatigue testing and end of life investigation of a topology optimized connecting rod fabricated via selective laser melting. *Int. J. Fatigue* **2022**, *164*, 107134. [CrossRef]