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LATTICE STRUCTURES GRADING FOR STIFFNESS OPTIMIZATION: AN APPROACH BASED ON TOPOLOGY OPTIMIZATION FOR PARTS MANUFACTURED VIA MULTI JET FUSION

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DOI: <https://doi.org/10.52152/D11298> | Recibido: 03/jul/2024 • Inicio Evaluación: 18/jul/2024 • Aceptado: 07/oct/2024

To cite this article: INNOCENTI, Alessandro; MORENO-NIETO, Daniel; BORGIANNI, Yuri; L. SALES, David; Molina, Sergio-I. LATTICE STRUCTURES GRADING FOR STIFFNESS OPTIMIZATION: AN APPROACH BASED ON TOPOLOGY OPTIMIZATION FOR PARTS MANUFACTURED VIA MULTI JET FUSION. DYNA. January February 2025. Vol. 100, n.1, pp. 63-69 - DOI: <https://dx.doi.org/10.6036/D11298>

ABSTRACT:

The rapid advancement of additive manufacturing (AM) technology and computational design techniques has unveiled a promising synergy between these two fields. The high print resolution achievable nowadays enables the production of intricate shapes, such as lattice structures, which can be further optimized through simulation-driven design techniques such as topology optimization (TO). This paper presents an optimization workflow that leverages field-driven design to employ the results of a TO to locally vary the diameter of lattice structures, aiming for weight reduction and stiffness maximization. The process involves the automation of nTop design software via Python scripts to systematically evaluate design variants and identify optimal solutions. The workflow steps are demonstrated through the application to a connecting rod and conclude with the evaluation of the achieved mechanical performance of the optimized component via Finite Element Method (FEM) analysis.

Keywords: Additive Manufacturing, Topology Optimization, Lattice Structures, Field-Driven Design, Finite Element Method.

FUNDING

INNANOMAT research group (TEP946; Junta de Andalucía).

1. INTRODUCTION

The recent development of additive manufacturing (AM) techniques and the growing interest in lightweighting mechanical components and achieving specific performance have fostered the establishment of advanced computational mechanical design techniques such as Topology Optimization (TO), Functionally Graded Lattice Structures (FGLs), and Field-driven Design [1]. These methods are usually referred to as simulation-driven techniques since they integrate computer simulations into early design stages to optimize components' performance: by exploiting data obtained from simulations, they automatically implement the required design improvements to control and ultimately optimize the performance.

The output shapes generated with such techniques are typically intricate and complex, making it challenging or even impossible to manufacture them using traditional methods. In this context, the various AM technologies offer a solution by allowing the creation of such intricate output shapes through a layer-by-layer approach. From this perspective, AM can be considered a catalyst for simulation-driven design techniques, as it unlocks the full potential of such methodologies [2]. At the same time, simulation-driven design can provide essential support for AM, particularly in design for additive manufacturing (DfAM) [3], where these tools help achieve key DfAM

	LATTICE STRUCTURES GRADING FOR STIFFNESS OPTIMIZATION: AN APPROACH BASED ON TOPOLOGY OPTIMIZATION FOR PARTS MANUFACTURED VIA MULTI JET FUSION	MECHANICS
RESEARCH ARTICLE	Alessandro Innocenti, Daniel Moreno Nieto, Yuri Borgianni, David L. Sales, Sergio I. Molina	Mechanical design methods

goals such as efficient material use and manufacturing process optimization [4]. In this respect, the proposed method will contribute to the field of DfAM as useful in the design and grading of lattice structures to optimize mechanical properties and material distribution, thereby improving the performance and efficiency of AM processes.

Due to their relevance to the proposed methodology, three of these simulation-driven design techniques, namely lattice structures and FGLs, field-driven design, and TO, are introduced in the following subsections.

1.1 LATTICE STRUCTURES AND FUNCTIONALLY GRADED LATTICE STRUCTURES

Lattice structures are three-dimensional periodic cellular patterns consisting of repeated unit cells that create regular patterns or stochastic formations (e.g., foams). Such structures are known for their high strength-to-weight ratios that make them particularly useful for lightweighting applications [5]. Furthermore, the wide variety of unit cell types makes it possible to achieve specific mechanical properties depending on the requirements of each case [6].

Lattice structures have been enhanced by AM that enabled their production with a wide range of materials. This advancement has broadened the range of potential applications for lattice structures in various industries such as automotive, aerospace, and medical. Furthermore, recent advancements of computational design methods are enabling the fine tuning of lattice structures by varying the volume fractions or other topological parameters of each unit cell in the 3D design domain. Such structures are referred to as FGLs and are characterized by locally changing material properties. This process, known as "lattice grading", involves varying lattice structure parameters like strut length, diameter, unit cell size, or wall thickness to create a functional gradient in the structure, allowing for tuning and optimization of material properties within the component's boundaries to achieve specific mechanical responses and minimize material consumption.

There are several ways for grading lattice structures, however they may be classified into three types based on the inputs used to drive such optimization:

1. **Function-driven:** employ mathematical functions for the variation of certain lattice parameters. For instance, in [7], a hybrid lattice structure is generated based on a mathematical function with three different regions to tailor the mechanical properties and improve osseointegration of a bone implant (Figure 1a).
2. **Data-driven:** potentially employ any kind of spatially varying data derived from simulations or experiments. For instance, local equivalent Von Mises stresses can be used to customize local properties of the lattice point by point as discussed in [8] (Figure 1b).
3. **Multi-scale TO:** apply a TO algorithm to optimize the lattice at two different levels: at the macroscopic level it focuses on the overall layout and arrangement of unit cells within the structure, while at the microscopic one, it optimizes the internal arrangement of struts within each unit cell. For example, in [9], the lattice structure of a custom pelvic prosthesis is graded employing a stress based TO (Figure 1c).

	LATTICE STRUCTURES GRADING FOR STIFFNESS OPTIMIZATION: AN APPROACH BASED ON TOPOLOGY OPTIMIZATION FOR PARTS MANUFACTURED VIA MULTI JET FUSION	MECHANICS
RESEARCH ARTICLE	Alessandro Innocenti, Daniel Moreno Nieto, Yuri Borgianni, David L. Sales, Sergio I. Molina	Mechanical design methods

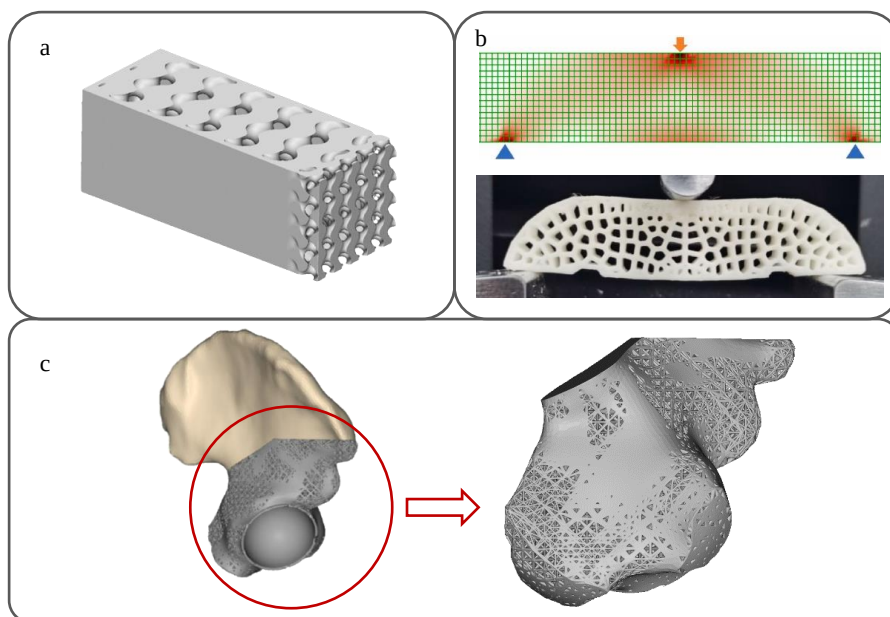


Fig. 1. (a) Hybrid lattice structure for osseointegration [7], (b) beam designed with data-driven graded lattice structures [8], (c) FGLs with multi-scale TO for implant design [9].

1.2 FIELD-DRIVEN DESIGN

Field-driven design is an engineering design tool that allows the user to exploit scalar/vector fields to control complex geometrical features such as lattice density or wall thickness of the design. Therefore, it can be seen as an extension of function-driven and data-driven FGLs grading methods. In fact, even if it is considered a powerful tool for the design of lattice structures, its possibilities go further as it is also possible to control various geometric features such as wall width, perforation patterns, surface textures and fillets. To control all these features, formulas, distances, test or simulation results, or other data could be used, allowing the user to directly modify the design based on the application [10].

This approach is not yet been treated extensively in literature, however there are some examples of case studies where it is employed. For instance, Ahmad et al. [11] used the equivalent Von Mises stress retrieved from a static simulation to design the lattice to optimize the mechanical performance of a horse saddle.

1.3 TOPOLOGY OPTIMIZATION

Topology optimization is a computational design method whose purpose is to optimize the distribution of material in a given design space with respect to the loads and constraints, while maximizing or minimizing specific parameters (e.g., weight, stiffness, stress, displacement etc.). Even if there are numerous techniques available for carrying out TO, they share the same concept to exploit data retrieved from simulations to iteratively remove or redistribute material within the boundaries of a component to achieve a specific design goal. At the end of the process, the TO platform provides as output the final optimized shape, which is usually organic and complex. Typical objectives in TO include minimizing mass and/or stress and increasing stiffness. Additionally, these methods can be utilized to attain specific mechanical behaviours in specific load scenarios. This technique in the past was considered mainly for academic purposes given the difficulty in producing the complex geometries obtained with it. However, due to developments in AM techniques, these algorithms have gained considerable attention in recent years in industry as well and TO modules have been integrated in some of the most important computer aided engineering (CAE) and computer aided design (CAD) software environments [12].

2. METHODS

In this section, the optimization workflow developed is presented. First, a case study is selected to apply the optimization method. Then, the general scheme of the optimization procedure is introduced along with the selection of the optimization software platform.

	LATTICE STRUCTURES GRADING FOR STIFFNESS OPTIMIZATION: AN APPROACH BASED ON TOPOLOGY OPTIMIZATION FOR PARTS MANUFACTURED VIA MULTI JET FUSION	MECHANICS
RESEARCH ARTICLE	Alessandro Innocenti, Daniel Moreno Nieto, Yuri Borgianni, David L. Sales, Sergio I. Molina	Mechanical design methods

Finally, with the aim of presenting the proposed method with a clear and systematic approach, the optimization workflow is presented step-by-step as it is applied to the selected case study.

2.1 CASE STUDY

To make this investigation meaningful, the component on which the optimization is performed represents a realistic industrial application, involving a three-dimensional connecting rod under bending.

Material selection. To make the optimization more streamlined, the material and manufacturing process must be selected to meet the following requirements:

1. The material should have no variation in Young's modulus in the different directions, as this greatly simplifies the optimization algorithms.
2. The printed part must be of high quality, to ensure an acceptable resolution on small features such as lattice structures.

Given these requirements, the material selected is polyamide 12 (PA 12), manufactured with Multi-Jet-Fusion (MJF), a powder bed AM technique that involves several steps, as schematized in Figure 2 [13].

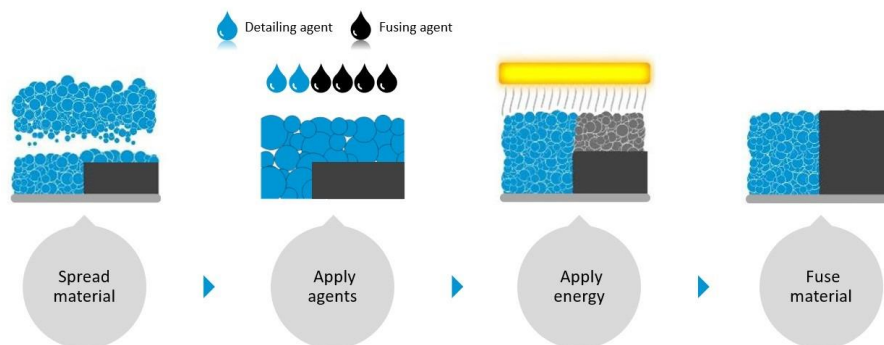


Fig. 2. Main MJF printing steps [13].

This technology, applied to PA 12, is particularly suitable to produce mechanical components with complex shapes as lattice structures [14]. In fact, it can print complex geometries and small features with high resolution with no need for support structures and the modulus of elasticity does not vary significantly with build orientation [15]. This choice allows to consider in the design and simulation phases the material as homogeneous and without defects with good approximation. Nonetheless, certain specific properties of the selected process add a manual design iteration needed to allow powder removal from the printed part.

With this approach, the obtained material properties are shown in Table 1.

Table 1. PA 12 printed with MJF properties.

Property	Value
Density [g/cm^3]	1.01
Tensile strength [MPa]	48
Tensile modulus [GPa]	1.7
Poisson's ratio	0.45

Boundary conditions and optimization objectives. The applied boundary conditions consist of a force of 17.15 N perpendicular to the component axis at one of its free ends and constraining the other end in the three directions, as shown Figure 3.

	LATTICE STRUCTURES GRADING FOR STIFFNESS OPTIMIZATION: AN APPROACH BASED ON TOPOLOGY OPTIMIZATION FOR PARTS MANUFACTURED VIA MULTI JET FUSION	MECHANICS
RESEARCH ARTICLE	Alessandro Innocenti, Daniel Moreno Nieto, Yuri Borgianni, David L. Sales, Sergio I. Molina	Mechanical design methods

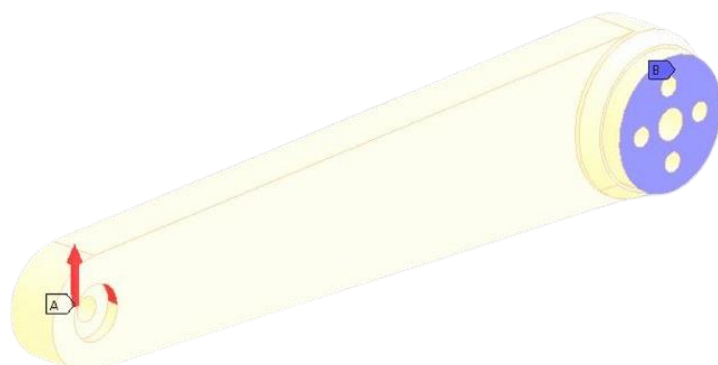


Fig. 3. Boundary conditions on initial design.

The main goal of the optimization was arbitrarily chosen to reflect what might be a common optimization case for such a component. Thus, it was set to minimize the vertical displacement of the tip of the component where the load is applied to maintain the rigidity and stability of the component. In addition, a total mass reduction of 25% with a tolerance of 1.75% was set, which is a realistic target for a lightweighting application.

2.2 OPTIMIZATION INTRODUCTION AND SOFTWARE SELECTION

The optimization method consists in replacing the solid interior of the part with FGLs with locally varying strut diameters. The internal lattice structure is then enclosed by a solid shell whose thickness has a constant value of 1.5 mm to provide sufficient structural support and allow easy fabrication with the chosen AM technique. The focus of the optimization is on the lattice infill, in which the diameter of the struts is locally graded based on a scalar field extracted from the density map of a TO performed on the initial part. The goal is to optimize the component by finding a more efficient redistribution of the mass used in the lattice structure. This approach aims to minimize vertical tip deformation while achieving the desired mass reduction.

Software selection. The nTop software [16], was chosen for this optimization process since it is one of the most widely used software for the design and optimization of lattice structures. This is due to its capability to easily design complex shapes with minimal computational burden. In addition, it is possible to create workflows that can then be automated using programming languages such as Python and MATLAB. This allows for the automation of design or optimization processes, providing considerable benefits for performing repetitive tasks.

Optimization. In the first step, a TO algorithm was used to generate a 3D map representing the optimum material distribution within the part to later control the lattice grading.

Topology Optimization. After importing the initial geometry into nTop, a Finite Element (FE) model of the component was built by meshing the geometry with quadratic tetrahedral elements and assigning the material properties defined in Table 1. The load case was then defined by connecting the load application point to the loaded faces with Rigid Body Elements 3 (RBE3) for a more uniform load distribution, as represented in Figure 4. Subsequently, the goal of optimization was set to minimize the compliance under the considered load case while constraining the final mass to 75% of the initial one.

	LATTICE STRUCTURES GRADING FOR STIFFNESS OPTIMIZATION: AN APPROACH BASED ON TOPOLOGY OPTIMIZATION FOR PARTS MANUFACTURED VIA MULTI JET FUSION	MECHANICS
RESEARCH ARTICLE	Alessandro Innocenti, Daniel Moreno Nieto, Yuri Borgianni, David L. Sales, Sergio I. Molina	Mechanical design methods



Fig. 4. FE model.

This software uses the Solid Isotropic Material with Penalization (SIMP) technique for TO [17]. SIMP is a density-based method based on the discretization of the design domain with a FE mesh. In this approach, each element is assigned a pseudo-density value (ρ) between 0 and 1, representing the presence or absence of material, where 0 is void and 1 is solid.

These density values are then iteratively adjusted to determine the ideal distribution of material within the structure, with each value influencing the physical properties of the corresponding element [18]. By applying this method to the studied component, the optimized map of pseudo-density values was returned. While in a traditional TO this map would control the presence or absence of material, in this workflow it was used to increase or decrease the thickness of the lattice beams, as visible in Figure 5.

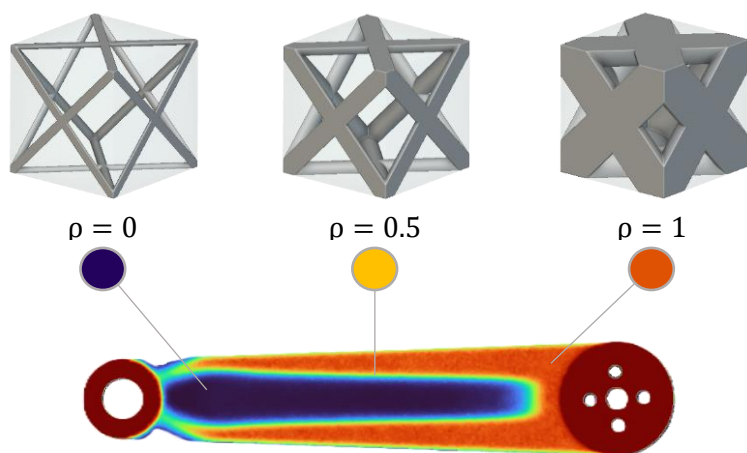


Fig. 5. Example of pseudo-density map's effects on lattice parameters.

Subsequently, a “ramp” block was used to rescale the map values from 0 to 1 into the actual lattice diameter values assigned to each element. Nonetheless, since the rescaled lattice parameters directly influence the lattice the overall mass, the resulting mass couldn't be known in advance. To ensure that only those parameter sets resulting in components with the desired target mass were selected, an nTop project was automated using Python scripts to filter the parameter combinations that produce components that met the specific target mass criteria.

nTop workflow automation via Python scripts. First, the range of various parameters evaluated was defined. These included 27 different combinations of unit cell sizes, 24 different strut diameter ranges, and 4 types of unit cells, for a total of 2592 different lattice structures. Specifically, the 24 different diameter ranges are all the combinations of the minimum and maximum diameter values shown in Table 2.

Table 2. Ranges of minimum and maximum lattice diameters values.

min. lattice diameter [mm]			Max. lattice diameter [mm]						
0.75	1	1.25	1.5	1.75	2	2.25	2.5	2.75	3

Through a series of loops implemented in the Python script, the parameter sets of each of these combinations were imported one at a time into nTop using “. json” files to exchange input and output data. Once the set of parameters were imported in nTop, the created workflow was automatically executed to build the model of the component with the lattice specifications received as input from the Python script. Then, it evaluated the component final mass and returned its value to the script. This value was read in Python, and if it was found to be equal to the target, the parameter set was stored.

This procedure was repeated in a loop to evaluate each one of the design variations, and finally, it would have stored only the parameter sets that met the restrictions imposed on the final mass. Finally, in a second Python script, the parameter sets stored were extracted and imported into another nTop file to perform a static structural FEM simulation for each one of them, as schematized in Figure 6. A more detailed description of the simulation setup and the Finite Element Analysis (FEA) models used in this algorithm is given in the following paragraphs.

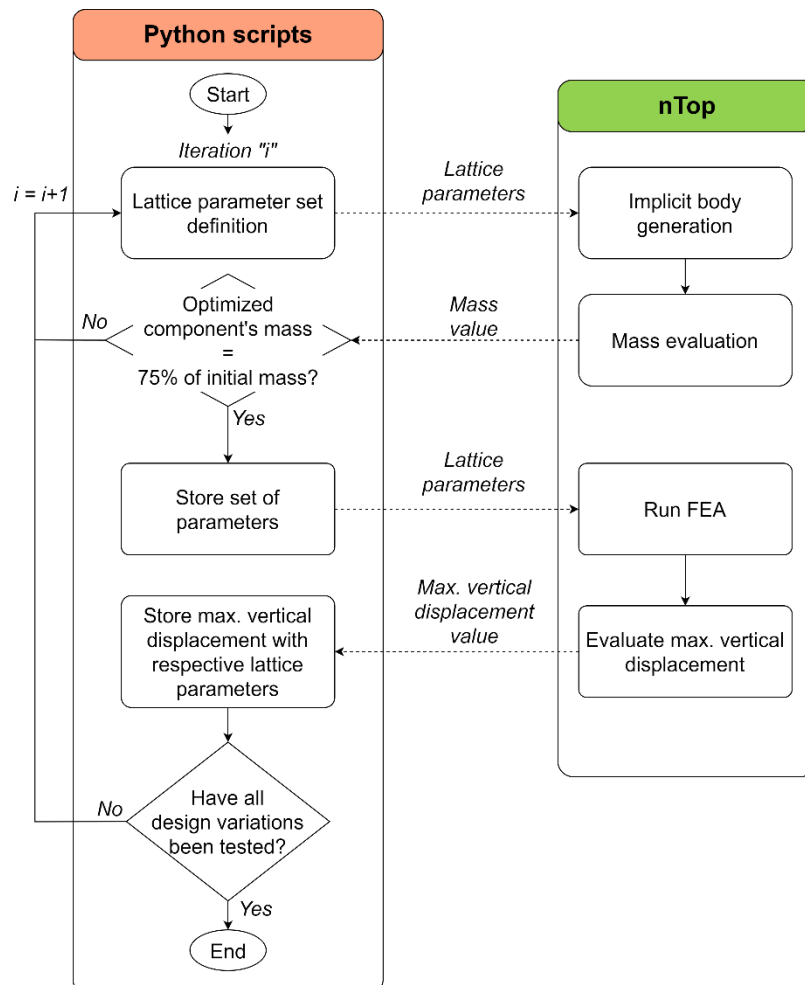


Fig. 6. Optimization workflow.

	LATTICE STRUCTURES GRADING FOR STIFFNESS OPTIMIZATION: AN APPROACH BASED ON TOPOLOGY OPTIMIZATION FOR PARTS MANUFACTURED VIA MULTI JET FUSION	MECHANICS
RESEARCH ARTICLE	Alessandro Innocenti, Daniel Moreno Nieto, Yuri Borgianni, David L. Sales, Sergio I. Molina	Mechanical design methods

FEA process description. Given the geometric complexity of lattice structures, the selection of an adequate FE model is a well-known challenge that is a current investigation topic. nTop provides three different methods for lattice simulation:

1. Use a solid volumetric mesh to model the lattice structure. This method is the most computationally demanding, as a very fine mesh with a high number of elements must be used. Nonetheless, it also provides the highest result accuracy, and it enables correct evaluation of edge effects and stress concentrations.
2. Employ 3D beam elements to simulate lattice trusses. While this approach greatly reduces the number of components compared to a solid volume mesh, it fails to capture edge effects and stress concentrations.
3. Replace the lattice unit cells with bulk unit cells made of a homogeneous material that has a comparable mechanical behaviour, evaluated through FEM.

To carry out the FEA within the automated process, the simplified model with beam elements was used to obtain a quick but still valid evaluation of the mechanical response. To apply the chosen modelling technique, the first step was to perform a mesh convergence analysis to make an optimal choice of mesh parameters. Next, a software function was used to extract directly from the implicit lattice structure the mesh composed of the corresponding beams, to which the respective strut diameter was then assigned. In nTop, the variable strut thickness is handled in the simple model by dividing each lattice truss into three beam elements, each characterized by a specific diameter based on the values provided by the ramp function. Furthermore, using the quadratic model for these elements results in an additional node at the centroid of each element, giving a total of 7 nodes and 3 elements for each truss, as shown in Figure 7.

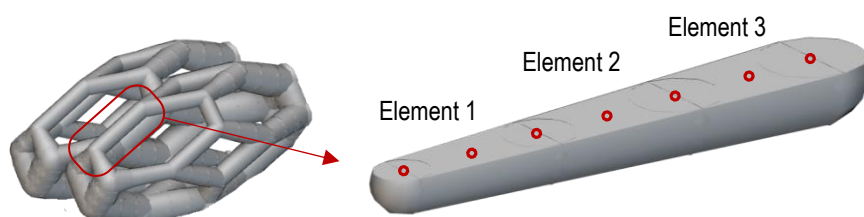


Fig. 7. FE element composition.

Once the FE model of the lattice structure was created, the nodes of the beam elements in contact with the outer shell mesh were rigidly linked to it. In this way, the solid mesh was merged with the lattice structure.

Based on the algorithm, for each parameter set given as input from the Python script, a FE model was built with the same boundary conditions and material properties specified for the TO, and a static structural analysis was performed. Once the computations finish, the simulation results are retrieved. In this way, each optimized component that met the mass constraint was simulated and the value of the maximum vertical deformation of its tip was retrieved and returned to the Python script. Finally, the result was opened in Python and stored together with the information of the respective lattice design parameters. Once all the iterations were executed, the process was concluded by returning a list of 156 possible designs that met the restrictions imposed on the mass along with the maximum deformation obtained for each.

Out of these, for each type of unit cell, the component with the least value of vertical deformation was selected for a total of 4 components. As shown in Figure 8, these were modelled using a full volumetric mesh and subjected to a static structural FEM simulation to:

- Obtain a more reliable value for the maximum vertical deformation.
- Compare the results obtained with the simplified model and those obtained with the full model.

	LATTICE STRUCTURES GRADING FOR STIFFNESS OPTIMIZATION: AN APPROACH BASED ON TOPOLOGY OPTIMIZATION FOR PARTS MANUFACTURED VIA MULTI JET FUSION	MECHANICS
RESEARCH ARTICLE	Alessandro Innocenti, Daniel Moreno Nieto, Yuri Borgianni, David L. Sales, Sergio I. Molina	Mechanical design methods

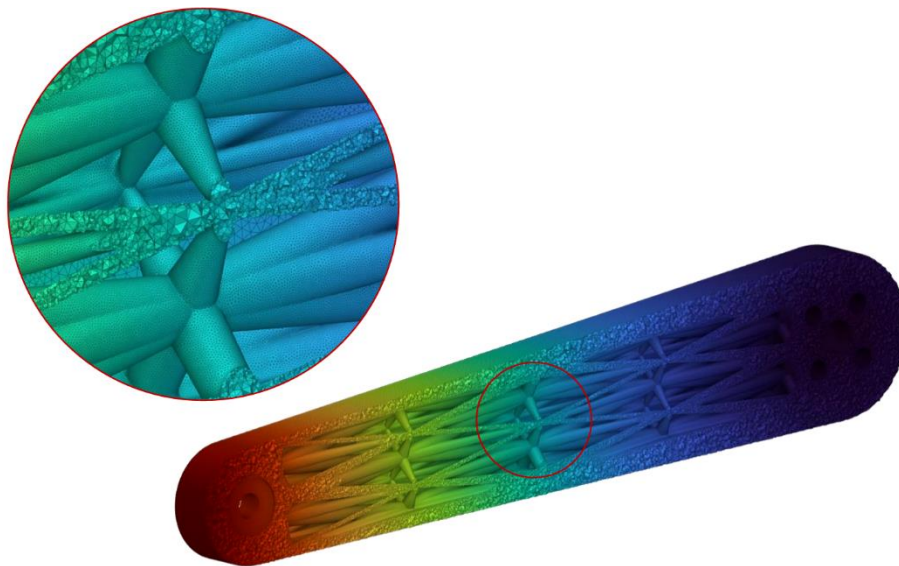


Fig. 8. Meshed component's static analysis result.

To set up the simulation, the same boundary conditions, and material of the TO were applied. Then, based on a mesh convergence analysis the mesh parameters were chosen, and the static structural analysis was performed. The deformation results obtained with the two methods were compared and used to determine the optimal design, that was the best lattice parameters combination that yielded the component with the minimum vertical tip deformation while respecting the mass constraints. Finally, to enable the component's production with the selected material and manufacturing technology, the design was edited to include holes for powder removal and simulated again with a full volumetric model to obtain the best evaluation of the maximum vertical deformation and mass.

3. RESULTS

The proposed optimization workflow yielded as output many design variations in which the component lattice infill was optimized by locally varying the diameter of the struts according to the TO density map through field-driven design. Among these, the ones that met the imposed mass constraint were filtered and the design that reported the best results in terms of vertical displacement was selected. Furthermore, employing the data retrieved from the FE simulations performed within the optimization workflow, it was possible to compare the deformation values results obtained with the simple and the full volumetric model for the best optimized designs, as shown in Table 3. This showed that the mean deviation between the values obtained with the two models is 7.6%.

Table 3. Simple and full model results.

Lattice type	Unit cell size [mm]			min. strut diameter [mm]	Max. strut diameter [mm]	Percent saved mass	Max. vertical deformation Simple model [mm]	Max. vertical deformation Full model [mm]
	x	y	z					
Face centered cubic	3.5	56.2	9.3	0.75	2.75	23.8	0.627	0.703
Octet	7.0	56.2	9.3	0.75	2.75	24	0.663	0.715
IsoTruss	7.0	56.2	9.3	1	2.75	23.8	0.680	0.717
Kelvin cell	3.5	56.2	9.3	1	2.5	24.1	0.678	0.712

To correctly evaluate the developed optimization workflow, it was essential to compute the mechanical response of the non-optimized component subjected to the same load case by performing a static structural FEM analysis. In this way, the initial mechanical performance could be used as a reference for a comparison with the optimized results.

	LATTICE STRUCTURES GRADING FOR STIFFNESS OPTIMIZATION: AN APPROACH BASED ON TOPOLOGY OPTIMIZATION FOR PARTS MANUFACTURED VIA MULTI JET FUSION	MECHANICS
RESEARCH ARTICLE	Alessandro Innocenti, Daniel Moreno Nieto, Yuri Borgianni, David L. Sales, Sergio I. Molina	Mechanical design methods

The static structural analysis was performed with the software ANSYS Workbench 2021 R2 [19]. After meshing the part based on a mesh convergence analysis, the same boundary conditions and material used for the optimized component were applied. Subsequently, the static analysis was performed, and the maximum value of vertical tip displacement, as well as the final component's mass was retrieved. Finally, it was possible to compare the obtained mechanical performance, in terms of mass and achieved tip vertical displacement of the optimized and initial component. This comparison is shown in Table 4.

Table 4. Mechanical performance comparison.

Design	Mass [g]	Saved mass [%]	Max. vertical deformation [mm]	Deviation of displacement from initial design [mm]	Deviation of displacement from initial design [%]
Initial	41.3	-	0.621	-	-
Optimized	31.3	24.2%	0.707	0.086	14%

4. DISCUSSION

This section summarizes and discusses the achieved mechanical performance and the most relevant features of the developed optimization workflow. The proposed method, by respecting the geometrical boundaries of the component and solely redistributing mass within the initial geometry achieved a reduction of 24.2% of the total mass, with only a slight increase in vertical deformation of 14%. Furthermore, the comparison between the results obtained from the simplified and full volumetric models indicates the robustness of the method used. In fact, the use of the simplified model is justified, at least for the simulations involved in the algorithm, to maintain an appropriate trade-off between computational effort and accuracy of the results, which in fact deviate on average by only 7.6% from those of the more accurate simulation model.

Finally, while applying the developed workflow, valuable insights were gained that allowed the identification of essential qualitative characteristics of the method. These findings, which are reported in the following paragraphs, are crucial for understanding its limitations, potential, and for ensuring its effective use.

4.1 MAIN CHARACTERISTICS

- The combination of Python scripts and nTop provides users with high control and scalability possibilities. The scripts can be adapted to handle various lattice structures and complex optimization problems by adjusting parameters, enabling customized optimization strategies.
- The method is relatively complex as it demands programming and software interaction skills. Automating advanced operations, such as TO and field-driven design, and modelling variable strut diameters, significantly increases the computing requirements, solution time and overall complexity of the process.
- The optimization process has limitations in finding an optimal solution as it does not rely on specific search algorithms for the lattice parameters selection. Therefore, a careful selection of lattice parameters during optimization setup is necessary to achieve the desired performance.
- The output geometries are smooth and ready for manufacturing since the process is based on the design tools available in nTop. However, certain post-processing operations, such as creating holes for powder removal, may be necessary to enable proper manufacturing.

5. CONCLUSION

This study presents a significant advancement in simulation-driven design techniques through the introduction of a novel workflow for lattice structure optimization. This approach is based on lattice grading with field-driven design using a TO pseudo-density map. Through the integration of Python scripts and nTop software, this workflow enables users to generate complex geometries optimized for specific mechanical performance requirements. By applying it to a real case study, a comprehensive analysis of the achieved mechanical performance and qualitative aspects was carried out, revealing its strengths and limitations. The main findings highlight that while the method offers high user control and scalability for tailor-made optimization strategies, it requires programming skills and is time consuming and computationally intensive. Overall, this study contributes to the development of the synergy between simulation-driven design techniques and additive manufacturing (AM), exploring new opportunities for lightweight and high-performance

	LATTICE STRUCTURES GRADING FOR STIFFNESS OPTIMIZATION: AN APPROACH BASED ON TOPOLOGY OPTIMIZATION FOR PARTS MANUFACTURED VIA MULTI JET FUSION	MECHANICS
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component design across various industries. In addition, it advances the field of DfAM by providing innovative approaches to the design and grading of lattice structures, further promoting efficient AM practices.

However, there are certain limitations that must be considered in order to properly interpret the results of this study, including the following:

- The proposed method was developed for the specific material and manufacturing process chosen. As a result, although the general structure of the method may be useful in a general sense, some different assumptions or steps may be required to make it suitable for other AM techniques.
- The case study was conducted on a specific simple component and therefore the results may not be applicable to all design scenarios. For this reason, there is no evidence of the validity of the method for more complex geometries and load scenarios, which are common in industrial design.
- The resulting mechanical behaviour from the simulations was not validated through mechanical testing, providing no evidence of the accuracy of the results obtained.

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ACKNOWLEDGEMENTS

We thank the INNANOMAT research group (TEP946; Junta de Andalucía) for the funding received to carry out this work, as well as the co-funding received from the European Union. We would also like to thank INGEGRAF for the funding provided.