Topology optimization with support structure filter for additive manufacturing

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Abstract. Topology optimization (OT) is an important tool in project design, aiming for maximum structural performance in terms of rigidity, strength, economy, and stability. However, the manufacturing of optimized structures using traditional methods is not always feasible due to the resulting geometric complexity. In this context, additive manufacturing (AM) emerges as a solution, enabling the production of objects layer by layer without the need for molds. This work studies topology optimization combined with a support structure filter (AMfilter), which includes a specific geometric constraint for AM. The objective is to analyze the feasibility of reducing the geometric complexity of structures while maintaining performance and minimizing the need for additional support material during the manufacturing process. The efficiency of the proposed approach is evaluated through 3D printing simulations using Fused Deposition Modeling (FDM) technology in the UltiMaker Cura 5.6 slicing software. The results show that, although the support structures were not completely eliminated, it was possible to reduce their amount, leading to more sustainable and cost-effective production using the AM technique.

Keywords: Topology optimization, Additive manufacturing, Fused Deposition Modeling, Support structure.

1 Introduction

Topology optimization is a mathematically-based technique widely employed in engineering for project analysis and design, applying optimization algorithms under specific problem constraints to achieve optimal structural performance. The process begins with a design domain, which encompasses the solution space, and ultimately delivers optimal solutions indicating which regions of the domain should be occupied by material and which should remain empty, considering mechanical criteria such as stiffness, strength, and stability, Eigel et al., [1]. This enables engineers to achieve lightweight, cost-effective, high-performance structures without compromising their integrity.

In this context, topology optimization stands out as an innovative method that transforms the concept of engineering design, offering solution freedom that often results in complex and unconventional design configurations, challenging traditional manufacturing methods. Consequently, additional treatments may be necessary to facilitate project execution, yet these often fall short of fully realizing the potential of topology optimization. In light of this perspective, additive manufacturing (AM) emerges as an advanced manufacturing technology that bridges the gap between optimized design and the physical fabrication of structures, Zhu et al., [2].

Additive manufacturing allows for the fabrication of geometrically complex parts without the need for additional tools or molds, building them layer by layer based on the three-dimensional geometric model. This provides greater autonomy in project development, enabling the design of economical and efficient products. Among its main technologies are Selective Laser Melting (SLM), Selective Laser Sintering (SLS), Metal Deposition (LMD), Fused Deposition Modeling (FDM), Selective Deposition Lamination (SDL), and Stereolithography (SLA). The primary difference between these technologies lies in the type of material used in manufacturing and how the layers are created and interconnected, Gibson et al., [3].

Despite the advantages of AM over traditional methods, there are still certain limitations. One of them, studied in the context of topology optimization, is the avoidance of designs with overhangs exceeding 45º angles, following the general rule of AM, Figueiredo [4]. Overhangs with angles greater than 45º (Fig. 1) are susceptible to gravitational forces during material deposition, which can lead to deformations or failures in part fabrication without adequate support. Conversely, the use of support structures impacts the final product quality, as their removal can cause surface damage or affect the part's mechanical integrity. Additionally, their use contributes to additional manufacturing costs, considering the time and amount of material involved, Kumar and Sathiya [5].

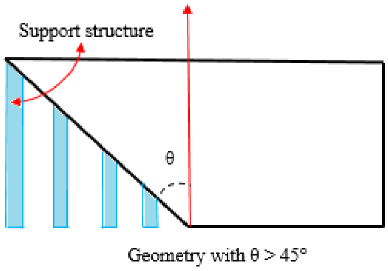


Figure 1. Example of geometries requiring support structures.

Therefore, besides the structural constraints initially considered in optimization problems, it is interesting to add constraints that address the limitations of AM. This approach allows engineers to obtain a final product that is not only structurally efficient but also feasible for the manufacturing process. This helps to minimize material and production time costs and maximize the final structure's quality and performance.

Thus, an academic contribution is proposed through the use of well-established educational codes for a better theoretical and practical understanding of the use of topology optimization algorithms and AM techniques. The study focuses on the use of topology optimization in conjunction with the support structure filter for AM, emphasizing the potential benefits of this practice in terms of material savings and production time. To this end, the methodology employs the 88-line educational code developed by Andreassen et al. [6] and the support structure filter for AM (AMfilter) developed by Langellar [7]. The performance and efficiency of this approach are evaluated through the 3D printing simulation of optimized models, based on the profile of FDM additive technology, one of the most popular techniques due to its simple manufacturing process and low initial investment, as described by Godec et al. [8]. For this evaluation, the UltiMaker Cura 5.6 slicing software is used, which is suitable for this type of technology, easy to configure, and free.

2 Methodology

2.1 Topology optimization code

For the development of this study, the educational 88-line code developed in MATLAB® by Andreassen et al. [6] was used as a basis. This code, widely available in the literature, provides an accessible educational interpretation for beginners in topology optimization. It explores different types of boundary conditions such as loading and support, cases involving multiple loads, and an example with a passive element.

In this article, however, only the classic examples of the symmetric Messerschmitt-Bölkow-Blohm (MBB) beam (Fig. 2a) and the cantilever beam with a passive element (Fig. 2b) are explored. The objective of the optimization problem is to find the optimal material distribution within the design domain to minimize compliance. For a comprehensive definition of the problems and additional details, it is recommended to refer to Andreassen et al. [6] and Sigmund [9].

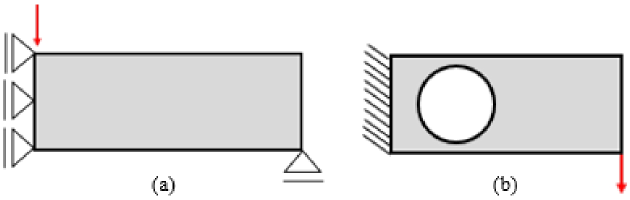


Figure 2. Examples of the design domains.

2.2 AMfilter

The AMfilter is a filter that implicitly incorporates a maximum projection angle of 45º as a geometric constraint for AM during the topology optimization process. In other words, the AMfilter simplifies the layer-by-layer printing technique by removing parts of the design that exceed the defined angle limit. This ensures that only solutions geometrically compatible with AM can be developed, aiming to eliminate the need for support structures and thereby minimizing operational manufacturing costs, Langelaar [7].

This filter was designed considering the principles of density-based topology optimization methods, which facilitates its integration into this methodology. In this method, the domain is discretized into a regular mesh of finite elements, where each element is associated with a density. During the optimization process, the AMfilter is the final filter used. It takes the design density field $\boldsymbol{\rho}$ as input and converts it into a new density field to be printed, denoted as $\bar{\boldsymbol{\rho}}$. Thus, the geometry described by $\bar{\boldsymbol{\rho}}$ is directly printed without the need for support structures. Further details about the AMfilter can be found in the study developed by Langelaar [7].

2.3 AMfilter implementation

The AMfilter is integrated into the topology optimization process of the 88-line code to verify its functionality and performance through the simulation of the aforementioned examples. To implement the AMfilter in the 88-line code, the recommendations described in Langelaar's research [7] were followed. The author highlights that, for the use of the Optimality Criteria (OC) algorithm employed in the 88-line code, an additional reduction of the "move" (m) parameter is necessary to better handle the non-linearity of the filter and facilitate problem convergence. Additionally, a new parameter called "baseplate" is included in the original code call. Thus, the code can be executed by providing the following information as input directly in the MATLAB® command prompt: “$top88(nelx, nely, volfrac, penal, r_{min}, ft, baseplate)$”.

The baseplate information defines the orientation of the base plate, which can be specified as North (N), East (E), South (S), West (W), or "X" to indicate the option of not using the AMfilter. This provides the user with greater flexibility in choosing the build orientation, a factor that also impacts the use of support material, in addition to the geometric characteristics of the structure itself.

2.4 3D printing simulation

To evaluate the functionality and efficiency of integrating the AMfilter with the topology optimization process, 3D printing simulations of the optimized models are conducted, considering the type of AM technology, FDM, since this technology requires support material in its manufacturing process and is one of the most accessible and popular in its use. Thus, the four print orientations (N, E, S, and W) of the optimized models are analyzed, with the slicing software configured to generate support at 45º, according to the constraint imposed by the AMfilter.

The slicing software used was UltiMaker Cura 5.6, a free tool that is easy to configure and suitable for the type of manufacturing technology adopted. The other settings for the simulation, such as layer height, extrusion width, wall thickness, infill, print speed, and print temperature, are, respectively: 0.2 mm; 0.4 mm; 1.2 mm; 15% (triangles); 45 mm/s; and 230°C.

In Fig. 3, a flowchart of the methodological procedures adopted in this research is presented, including the software and platforms used.

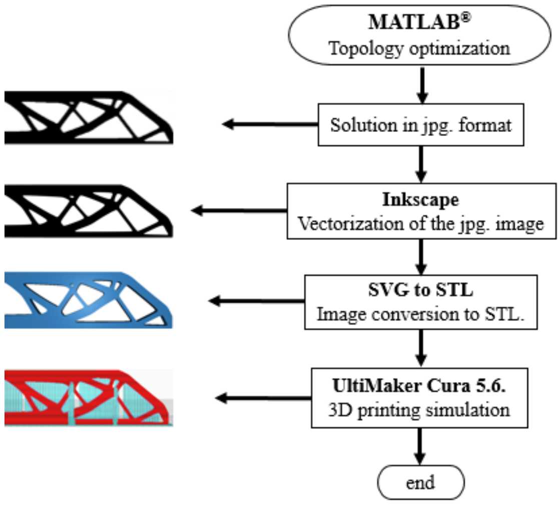


Figure 3. Flowchart of the adopted methodology.

3 Results

3.1 Example of MBB beam

The design domain presented in Fig. 2a is discretized into a finite element mesh of 720 x 240. The input data for the optimization problem are as follows: a density filter with a radius width, $r_{min} = 8$; a volume fraction, $volfrac = 0{,}5$; a penalization factor, $penal = 3$; and $ft = 2$ (density filter). The material properties remained the same as defined in the 88-line code: modulus of elasticity ($E = 1$), Poisson's ratio ($\nu = 0{,}3$) and a minimum stiffness ($E_{min} = 10^{-9}$).

Furthermore, the following input parameters for AMfilter were defined: $\xi_0 = 0{,}5$; $P = 80$; and $\varepsilon = 10^{-3}$. The parameter ξ_0 defines the penalization of elements with low density, while P and ε control the smoothness and precision of the solution approximation.

It is important to highlight that, in this study, it was necessary to adjust the P and ε parameters used in Langelaar's article [7] to the values mentioned above in order to achieve convergence of the results using the OC optimization algorithm. In Langelaar's article [7], a different algorithm known as the Method of Moving Asymptotes (MMA) was used, and the values of P and ε were smaller. This suggests a sensitivity in the filter parameter settings concerning the type of optimization algorithm employed.

In Fig. 4, the optimization solutions are presented, where a similarity in topology is noticeable between the models that used the AMfilter and the reference model (Fig. 4a) that did not use the filter during the optimization process.

(a) Ref. model $c = 203{,}90$

(b) Orientation ‘W’ $c = 201{,}66$

(c) Orientation ‘E’ $c = 201{,}85$

(d) Orientation ‘N’ $c = 210{,}73$

(e) Orientation ‘S’ $c = 207{,}15$

Figure 4. Optimized solution of the MBB beam model.

The designs in orientations ‘N’ and ‘S’ are shown to be less efficient, exhibiting an increase in compliance (c) value compared to the reference model. In other words, these structures are less rigid and deform more easily under applied load. Additionally, an irregular build-up of material is observed in the printing direction. This occurs because, with the inclusion of the AMfilter, the optimization algorithm attempts to create a manufacturable design. The optimizer seeks to form a support element for the beam along its entire horizontal span, but is not entirely successful in this task, resulting in irregularities in the lower and upper regions of the ‘N’ and ‘S’ models, respectively.

On the other hand, the models in orientations ‘E’ and ‘W’ demonstrate superior performance compared to the reference model, showing the lowest compliance values. This result is intriguing, as the expectation was that these models would have higher compliance due to the application of an additional constraint in the optimization process. This is likely due to the non-convexity of the problem. However, the 'W' orientation stood out as the most efficient, maintaining desired performance without losing rigidity, making it a viable option for printing without the need for support structures.

When analyzing the 3D printing simulation of these models (Fig.5), it is noticeable that the AMfilter did not completely eliminate the need for support structures for FDM technology in UltiMaker Cura 5.6 slicing software, as they are present in all printing orientations, visible in cyan color. However, data from Table 1 show a minimal reduction of 37 minutes in support structure print time for the 'W' orientation AMfilter model compared to the reference model in the same orientation. Although both topologies are similar, the internal element angulation in the AMfilter model results in a smaller support region, as analyzed by the slicing software.

As expected, the AMfilter models in 'N' and 'S' orientations are not suitable for additive manufacturing, resulting in higher material demand and longer print times (Table 1). In this scenario, the reference model 'S' is the most advantageous in practice, as it consumes less material and print time. Thus, the use of AMfilter in the optimization process resulted in inefficient solutions for this example.

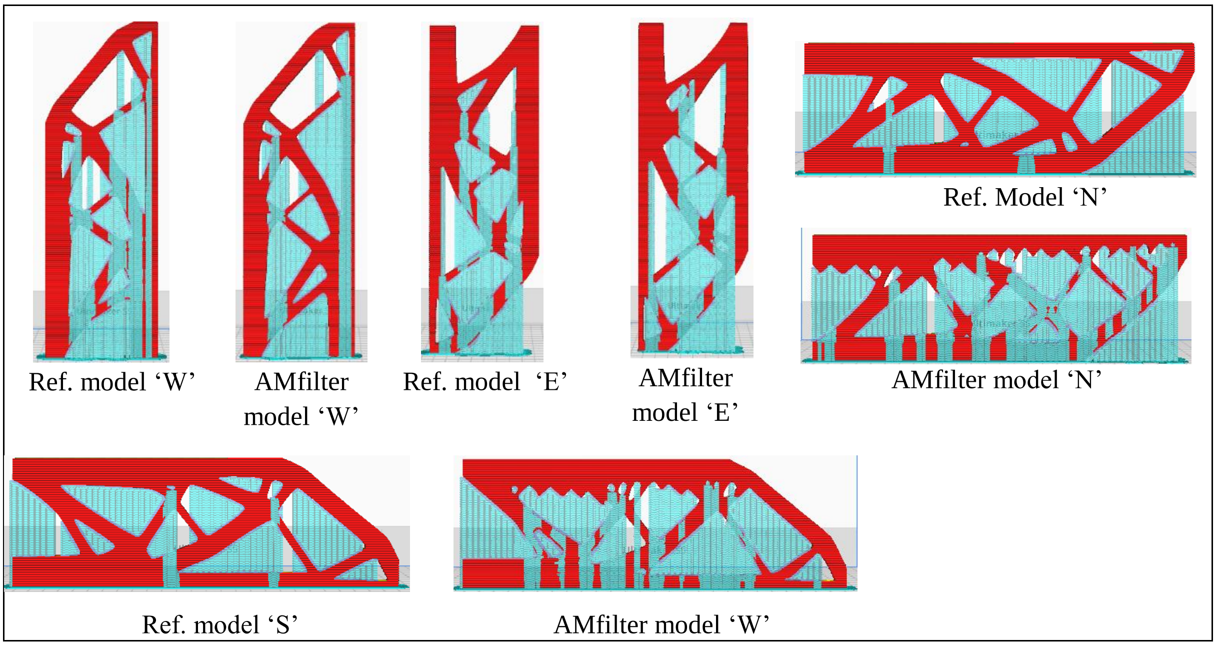

Ref. model 'W'
AMfilter model 'W'
Ref. model 'E'
AMfilter model 'E'
Ref. Model 'N'
AMfilter model 'N'
Ref. model 'S'
AMfilter model 'W'

Figure 5. 3D printing simulation of the MBB beam, with support generation for angles greater than 45°.

Table 1. Data from the MBB beam printing simulation.

Models	Total printing time	Material	Support structure printing time
Ref. model 'W'	21hr 11min	96g	5hr 48min
AMfilter model 'W'	19hr 21min	91g	5hr 11min
Ref. model 'E'	20hr 20min	91g	4hr 44min
AMfilter model 'E'	20hr 30min	91g	5hr 03min
Ref. model 'N'	19hr 13min	95g	5hr 23min
AMfilter model 'N'	25hr 30min	112g	8hr 05min
Ref. model 'S'	18hr 14min	90g	4hr 40min
AMfilter model 'S'	21hr 58min	100g	6hr 21min

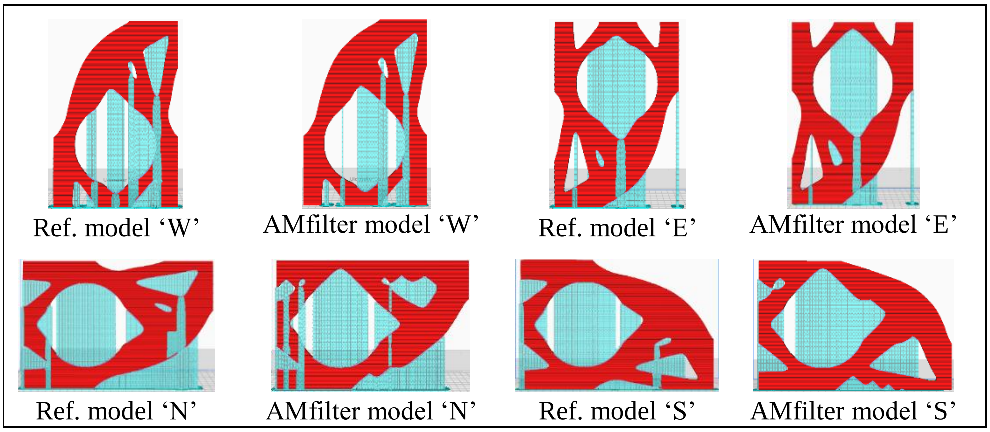
3.2 Example of a cantilever beam with passive element

In this case, the design domain (Fig. 2b) is discretized into a finite element mesh of 450 x 300. A density filter with $r_{min} = 15$ is used, and the remaining parameters, including those of the AMfilter, were applied as in the previous example. In Fig. 6, the resulting optimization solutions are illustrated, showing a similarity in topologies, although the models in ‘S’ and ‘N’ orientations exhibit more pronounced distinctions in their topology. Models in these orientations, similar to the previous example, stand out for having higher compliance values, being less efficient compared to the reference model that does not use the AMfilter. On the other hand, models in ‘W’ and ‘E’ orientations are highlighted as the most efficient and viable options for AM.

(a) Ref. model $c = 57{,}04$ (b) Orientation ‘W’ $c = 56{,}04$ (c) Orientation ‘E’ $c = 56{,}34$ (d) Orientation ‘N’ $c = 65{,}27$ (e) Orientation ‘S’ $c = 68{,}74$

Figure 6. Topology optimization solution of the model with passive element.

The 3D printing simulation of these models (Fig. 7) shows that topology optimization, combined with the AMfilter, also did not completely eliminate the need for support structures. However, there was a significant reduction of 1hr 10min in the support structure printing time for the 'W' AMfilter model compared to the reference 'W' model. This is due to changes in geometry, particularly in the angulation of the circular region at the center of the structure, where the circular area is tapered in the printing direction, reducing the need for support. The other models also show a slight reduction in both printing time and material usage, except for the 'S' AMfilter model, which performed worse than the reference model, as indicated by Table 2.



Ref. model ‘W’ AMfilter model ‘W’ Ref. model ‘E’ AMfilter model ‘E’

Ref. model ‘N’ AMfilter model ‘N’ Ref. model ‘S’ AMfilter model ‘S’

Figure 7. 3D printing simulation of the model with passive element, with support generation for angles greater than 45°.

Table 2. Printing simulation data of the model with passive element.

Models	Total printing time	Material	Support structure printing time
Ref. model ‘W’	26hr 14min	144g	7hr 02min
AMfilter model ‘W’	24hr 03min	134g	5hr 52min
Ref. model ‘E’	25hr 21min	142g	6hr 44min
AMfilter model ‘E’	24hr 28min	137g	6hr 17min
Ref. model ‘N’	30hr 45min	165g	10hr 22min
AMfilter model ‘N’	30hr 40min	163g	10hr 21min
Ref. model ‘S’	27hr 19min	153g	8hr 09min
AMfilter model ‘S’	271hr 57min	154g	8hr 37min

Comparing the results of examples 4.1 and 4.2, it is observed that the use of AMfilter in example 4.2 resulted in superior performance. The AMfilter managed, within the constraints of the problem, to limit the regions that would require support structures, promoting more significant changes in topology. This is more noticeable when comparing the data in Tables 1 and 2.

4 Conclusions

The implementation of the AMfilter in the topology optimization process based on the density method resulted in solutions aligned with the expectations for this type of approach, where the topologies configure the optimal material distribution based on the problem's set of constraints. With the use of the AMfilter, small modifications in the resulting topology are observed, favoring not only structural performance but also the possibility of manufacturing without the need for support structures.

However, when using the slicing software UltiMaker Cura 5.6 for FDM technology, the solutions obtained by the AMfilter did not fully meet the expectations of eliminating additional support structures. Despite enabling a slight reduction in the use of these structures and contributing to a more sustainable and economical production, this is better observed in the example of a cantilever beam with a passive element.

Additionally, with the implementation of the AMfilter, the optimization problem becomes more complex. This may have influenced the need for adjustments in the values of the filter parameters P and ε, which control the accuracy and smoothness of the solution approximations. The use of these approximations can introduce numerical errors, which must be carefully considered. Therefore, future studies can focus on optimizing these parameters and adapting the techniques to improve the obtained solutions, aiming for a balance between structural performance and manufacturing efficiency.

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References

[1] M. Eigel; M. Haase; J. Neumann, "Topology optimization under uncertainties with neural networks". *Algorithms*, vol. 15, pp. 1-34, 2022.
[2] J. Zhu; H. Zhou; C. Wang; L. Zhou; S. Yuan; W. Zhang, "A review of topology optimization for additive manufacturing: status and challenges". *Chinese Journal of Aeronautics*, vol. 34, n. 1, pp. 91-110, 2021.
[3] I. Gibson; D. Rosen; B. Stucker, *Additive manufacturing technologies: 3D printing, rapid prototyping, and direct digital manufacturing*. Springer, 2015.
[4] M. Figueiredo, *"*Estrutura de suporte à manufatura aditiva: por que são importantes e como projetar para elas*"*. Disponível em: https://www.manufaturadigital.com/estruturas-de-suporte-manufatura-aditiva/. 2022.
[5] M. B. Kumar and P. Sathiya, "Methods and materials for additive manufacturing: a critical review on advancements and challenges". In: SILVESTE, N. (Org.). Thin-Walled Structures. Elsevier, 2020.
[6] E. Andreassen; A. Clausen; M. Schevenels; B. S. Lazarov; O. Sigmund, "Efficient topology optimization in MATLAB using 88 lines of code". *Struct Multidisc Optim.*, vol.43, pp. 1-16, 2010.
[7] M. Langelaar, "An additive manufacturing filter for topology optimization of print-ready designs". *Struct Multidisc Optim.*, vol. 55, pp. 871-883, 2016.
[8] D. Godec; A. Pilipovié; T. Breski; J. Urena; O. Jordá; M. Martínez; J. Gonzales-Gutierrez; J. R. B. Schuschnigg; L. Portolés, "Introduction to additive manufacturing". In: D. Godec; J. Gonzales-Gutierrez*;* A. Nordin; E. Pei; U. J. Alcázar. (Org.) *A guide to additive manufacturing*, pp. 1-43, Cham: Springer, 2022.
[9] O. Sigmund, "A 99 line topology optimization code written in Matlab". *Struct Multidisc Optim*, vol. 21, pp.120-127, 2001.