Title:
**Topology Optimization Within a Variable Design Domain**

Authors:
Aljaž Žafran, aljaz.zafran@fs.uni-lj.si, University of Ljubljana
Nikola Vukašinović, nikola.vukasinovic@fs.uni-lj.si, University of Ljubljana

Keywords:
Topology Optimization, Variable Design Domain, Design Space Exploration, Concept Design

DOI: 10.14733/cadconfP.2025.104-109

Introduction:

Topology optimization provides the optimal geometry for a specific combination of precisely defined design or input parameters, such as the shape and size of the initial design domain, loading conditions, boundary constraints, etc. If one of these parameters changes, a different optimal solution is obtained.

Topology optimization has most often been used to optimize the geometry of existing designs, primarily focusing on reducing mass while maintaining the necessary structural strength for efficient use of material. In this case, all the information (input parameters) required to perform topology optimization is usually available. In recent years, topology optimization has gained traction as a tool for the development of new design solutions already in the concept development phase of the product development chain [1, 5]. In many early development processes, however, the input parameters are not yet defined with values, but are specified as ranges of values. This leaves the engineer with a broad design space to explore and it is usually not clear which value for each input parameter will give the best final solution. Furthermore, the interactions between the input parameters and their effects on the final optimized geometry can be very complex when dealing with problems with several variable input parameters. Even in scenarios where the design parameters have already been fixed, it is not known whether the result is optimal. Possible better optimized geometries and new concepts are a sufficient incentive to explore larger design spaces.

Due to the high computational demands of topology optimization, it is impractical to evaluate a lot of possible parameter combinations. To address this problem, we were inspired by the principles of design of experiments and evaluated only selected combinations of input parameters and their effects on the mass of the optimized geometry in two case studies. We also evaluated the increased time cost required for such an exploration of the design space.

Related work:

Several researchers have addressed the problem of finding the optimal input parameters for topology optimization. For example, Rong et al. [4] proposed a method that uses an adaptive design domain that automatically evolves the size of the design domain in which the material is distributed during topology optimization. Al Ali and Shimoda [2] investigated the influence of the shape of the initial design domain in the context of concurrent multi-scale topology optimization for heat conductivity maximization. The work of Maruyama et al. [3] is the most related to the topic at hand. They investigated optimization on two levels. They performed multiple topology optimizations with varying initial design domain and then used metamodeling to determine the optimal values of "external variables" (position of boundary conditions, shape of the design domain) , as opposed to the one-step formulation approach used by other researchers (e.g. [6]). However, this approach requires results of many topology optimizations to create accurate metamodels, which would be time-consuming for larger, more complex problems. The computational cost of metamodeling with many dimensions is also a factor that would make the proposed framework difficult to use in the development process of complex products where resources are limited.

Methodology:

First, we determined how many combinations of input parameters and their values should be tested for each case. A good analysis of the problem is important, as some parameters influence the final solution more than others and could lead to narrowing down the ranges of variables with good intuition. However, we have considered the full ranges of parameters to simulate "worst case" scenarios where several topology optimizations could be performed after the best result has already been achieved, making them redundant.

Once all parameter combinations were chosen, we used SpaceClaim to create geometries for initial design domains. A structural analysis with given loads was performed in Ansys Mechanical, followed by a topology optimization for each initial design domain. The optimized geometries were then exported to SpaceClaim, where any problematic geometries were corrected and prepared for validation. Structural analysis of the final geometries were performed in Ansys Mechanical under the same loading conditions as for the initial design domains. Optimized geometries that did not satisfy set constraints were corrected until they passed the validation phase. Since we are only interested in the solution with the lowest mass, it would make sense to check only the best result of the topology optimization. For comparison purposes, we validated all results.

We compared these results with the use of topology optimization without searching the entire design space. Since the optimal values for the input parameters are not known in advance, we have to choose them "blindly". One could argue that it might be most obvious or intuitive to simply choose the initial design domain with the largest volume. This means that topology optimization would remove more material if we consider % of the initial volume. However, a larger % of removed material does not necessarily yield a solution with the least mass.

All work was performed on a computer with Intel Core i7-8750H CPU, 8 GB RAM and Ansys Student 2024 R1 software.

Case Study 1:

In the first case study, we examined a simple beam that is fixed at one end and loaded at the other. The problem is two-dimensional and only one parameter is varied. The initial design domain has a hole with a diameter of 40 mm, which is 50 mm away from top and side edges, as shown in Figure 1. The length of the top edge is 100 mm. The length of the side edges (L) can be in the range of up to 140 mm. Two 10 mm edges are provided as a fixed support. A force of 2 kN is distributed over 10 mm of the top edge at the end. The material was structural steel with a modulus of elasticity of 200 GPa, a Poisson's ratio of 0.3, a density of 7850 kg/m$^3$ and a yield strength of 250 MPa.

We used SIMP (Solid Isotropic Material with Penalization) method with a penalty factor of 3. Regions of boundary conditions were excluded from the optimization. Topology optimization objective function is usually set to minimize compliance, but since we wanted to find light solutions, we set objective function to mass minimization. The response (optimized geometry) was constrained either by global equivalent (von-Mises) stress or displacement in the direction of applied load. Since we do not know which constraint will be critical, we set up both and the algorithm will stop reducing mass once it reaches limit of one constraint. The maximum global stress was set to 100 MPa and the maximum displacement to 0,5 mm. The size of the elements was set to 1 mm. For the solution, element retention threshold was set to 0,4. In this way, we obtain a more conservative solution that slightly increases the safety factor of the

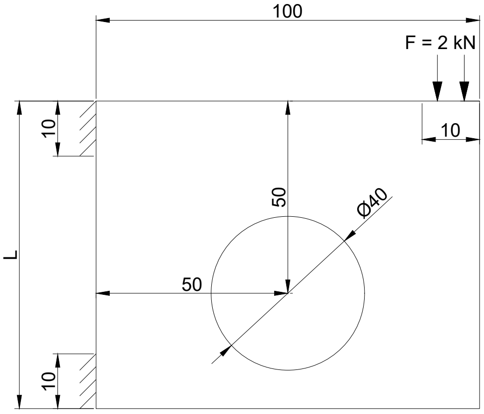


Fig. 1: Sketch of initial design domain in case study 1.

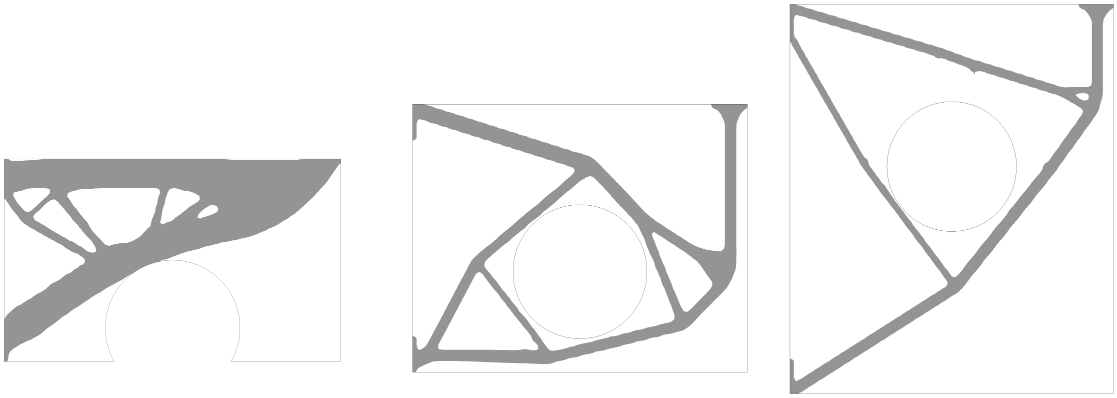

Fig. 2: Examples of optimized geometries of different initial design domains in case study 1.

structure. Post-processing is also generally easier as the structural elements are thicker and less likely to be disconnected.

The topology optimizations were performed starting from the smallest possible L = 20 mm with increases of 20 mm. It was impossible to obtain results because the maximum stresses in the case of L = 20 mm already exceeded 100 MPa before optimization. For the cases from 40 to 140 mm, the topology optimization took from 1 minute and 39 seconds for design domain 1 up to 7 minutes and 29 seconds for design domain 7. All results were acceptable in the validation phase. Post-processing and validation took about 10 to 15 minutes per geometry. The best solution had a mass of 0,088 kg at L = 120 mm, as can be seen in the table 1. Some examples of optimized geometries can be seen in Figure 2.

The time required to perform the topology optimizations and validate all structures was 90 minutes in total. 40 minutes were needed when performing all topology optimizations and validating only the best solution. Performing the topology optimization and validation for only the largest design domain took 17 minutes. The time is rounded to the nearest minute and assuming that 10 minutes were needed for each validation. Performing six topology optimizations and validating only the best solution required about 2,3 times as much time as a single topology optimization for the largest design domain. With searching

| Design domain | L [mm] | Time [min : s] | Starting mass [kg] | Final mass [kg] |
|---|---|---|---|---|
| 1 | 20 | / | 0,157 | / |
| 2 | 40 | 01 : 39 | 0,295 | 0,178 |
| 3 | 60 | 02 : 37 | 0,392 | 0,167 |
| 4 | 80 | 04 : 36 | 0,529 | 0,110 |
| 5 | 100 | 06 : 22 | 0,686 | 0,100 |
| 6 | 120 | 06 : 51 | 0,843 | 0,088 |
| 7 | 140 | 07 : 29 | 1,000 | 0,095 |

Table 1: Results of the 2D case

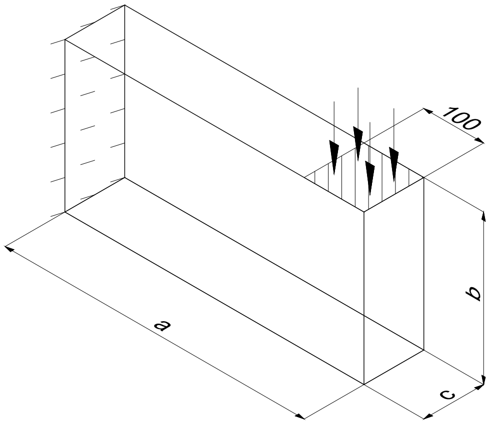


Fig. 3: Sketch of the initial design domain for case study 2.

the entire possible design space we achieved a solution at L = 120mm with a mass of 0,088 kg, which is a reduction of 7,4 % compared to a 0,095 kg solution we obtained from the largest design domain.

Case Study 2:

For the second case study, we analyzed a beam structure attached to a wall at one end and subjected to a load of 20 kN at the other end. The structure can be seen in Figure 3. The initial design domain for the beam was a prism with three dimensions: Length ($a$), Height ($b$) and Width ($c$). Length of the beam is precisely defined, while height and width were specified as ranges. The height can vary between 150 mm and 450 mm, while the width is between 100 mm and 200 mm. The material is the same as in the previous case

We again used SIMP method with the same configuration as before. The difference was in set constraints, where we restricted the geometry to maximum global stress of 167 MPa and maximum deformation of 0.5 mm. The size of the finite elements was 10 mm. In addition, symmetry was taken into account to reduce computational costs.

We assumed that the dimension (b) varying in the load direction would have a greater influence on the mass reduction of final geometry. It also has a larger range than the width (c). Therefore, four values were chosen for the height and two for the width. We took inspiration from the full factorial design and performed 8 topology optimizations, checking each combination of values. Most of the geometries obtained were acceptable right away, in some cases a correction was needed due to thin or sharp geometry.

Proceedings of CAD'25, Shenzhen, China, June 23-25, 2025, 104-109

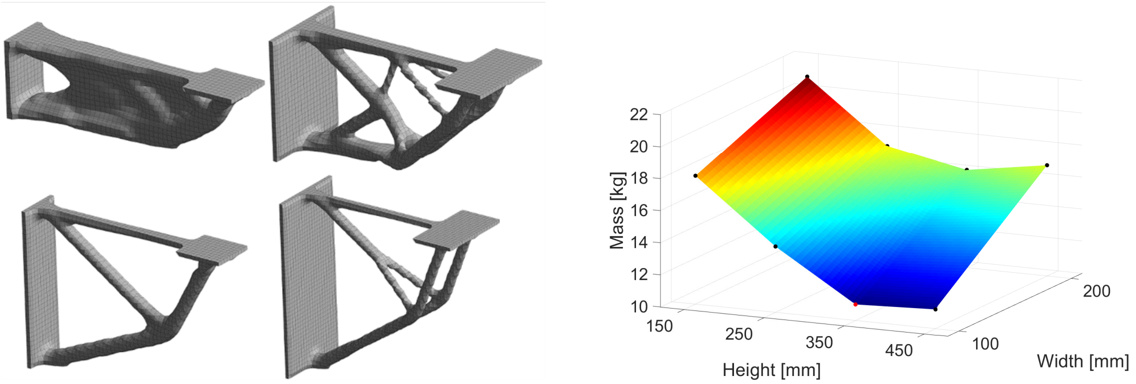


Fig. 4: Left: examples of optimized geometries of different initial design domains; Right: effect of height and width of initial design domain on mass of the optimized geometry.

| Design domain | Height [mm] | Width [mm] | Time [min : s] | Starting mass [kg] | Final mass [kg] |
|---|---|---|---|---|---|
| 1 | 150 | 100 | 02 : 01 | 58,9 | 18,0 |
| 2 | 150 | 200 | 04 : 43 | 117,8 | 20,9 |
| 3 | 250 | 100 | 04 : 49 | 98,1 | 14,1 |
| 4 | 250 | 200 | 11 : 37 | 196,3 | 17,1 |
| 5 | 350 | 100 | 07 : 28 | 137,4 | 11,0 |
| 6 | 350 | 200 | 17 : 52 | 274,7 | 16,1 |
| 7 | 450 | 100 | 08 : 31 | 176,6 | 11,2 |
| 8 | 450 | 200 | 23 : 38 | 353,2 | 16,9 |

Table 2: Results of the second case study

Examples are shown on the left side of the figure 4.

Topology optimizations required from 2 minutes and 1 second for design domain 1 up to 23 minutes and 38 seconds for design domain 8. Post-processing and validation took on average about 30 minutes per solution. The resulting structures had masses between 11.0 and 20.9 kg, as can be seen in table 2. Parameters of design domain 5 resulted in the lightest solution. Figure 4 on the right also shows a graphical representation of the interaction between height, width and mass of the optimized geometry.

The total time spent, rounded to the nearest minute, was 321 minutes for the validation of all structures and 111 minutes when validating only the best solution, assuming 30 minutes for each validation. Performing only one topology optimization and validation of only the largest design domain took 54 minutes. Note that we did not include the time needed to prepare the geometry and settings for topology optimization. This is due to the fact that scripts for such repetitive tasks can be easily implemented, making the time cost negligible, especially when a larger number of topology optimizations are performed. However, when performing single topology optimization the time needed for initial geometry preparation could represent a more significant portion.

Performing 8 topology optimizations and validating only the best solution required approximately twice the time compared to a single topology optimization of the largest design domain. With this approach, an optimal geometry with a mass of 11.0 kg was obtained, which represents a reduction of 34.9 % compared to the 16.9 kg solution from the largest design domain. We also obtained several design concepts that offer a wider range of options for further development.

Conclusions:

By systematically evaluating possible combinations of input parameters for topology optimization, we obtained several different optimized geometries. If we perform multiple topology optimizations and validate the best solution, we have a good chance of finding geometries with lower mass. In addition to achieving a lighter solution, this provides multiple design concepts that offer more options for further development. The disadvantage of such exploration of design space is increase in time costs.

We could reduce the time costs by taking into account the intuition of the engineer who can narrow down the initial ranges of input parameters. The number of topology optimizations could also be reduced during the process if we see that the remaining combinations are unlikely to offer any improvement. Another way to possibly reduce the number of topology optimizations required for an efficient exploration of the design space would be to draw inspiration from fractional factorial design.

We compared our method with a topology optimization result of the largest design domain in each case study to show that we have good possibility to find better solutions. Compared to Maruyama et al. [3], we performed fewer topology optimizations. While they performed over 100 topology optimizations to construct their metamodels for some cases, we performed up to 8. For a more accurate comparison of the results obtained and the number of topology optimizations required to achieve similar results to their method, we need to construct metamodels, which would be computationally expensive in our case. In the future, we want to compare our work with their method by using high performance computing (HPC) for topology optimizations and on problems with more variables.

Acknowledgement:

The research was supported by the Slovenian Research and Innovation Agency as part of the research programme P2-0425 "Decentralized solutions for the digitalization of industry and smart cities and communities" and Young Researcher Programme.

*Aljaž Žafran*, https://orcid.org/0009-0001-6974-4310
*Nikola Vukašinović*, https://orcid.org/0000-0003-4708-0469

References:

[1] Ahmad, A.; Bici, M.; Campana, F.: Guidelines for Topology Optimization as Concept Design Tool and Their Application for the Mechanical Design of the Inner Frame to Support an Ancient Bronze Statue, Applied Sciences 11(17), 2021, 7834. https://doi.org/10.3390/app11177834

[2] Al Ali, M.; Shimoda, M.: Exploring the influence of initial design domain dependencies in concurrent multiscale topology optimization for heat conductivity maximization, Computer physics communications, 295, 2024, 108968. https://doi.org/10.1016/j.cpc.2023.108968

[3] Maruyama, S.; Yamasaki, S.; Yaji, K.; Fujita K.: Topology optimization incorporating external variables with metamodeling, Structural and multidisciplinary optimization, 62, 2020, 2455-2466. https://doi.org/10.1007/s00158-020-02616-1

[4] Rong, Y.; Zhao, Z. L.; Feng X.-Q. ;Xie, Y. M.: Structural topology optimization with an adaptive design domain, Computer Methods in Applied Mechanics and Engineering 389, 2022, 114382. https://doi.org/10.1016/j.cma.2021.114382

[5] Vlah, D.; Žavbi, R.; Vukašinovic, N.: Evaluation of topology optimization and generative design tools as support for conceptual design, Proceedings of the Design Society: DESIGN Conference, 2020, 451-460. https://doi.org/10.1017/dsd.2020.165

[6] Zhu, J. H.; Zhang, W. H.: Integrated layout design of supports and structures, Computer Methods in Applied Mechanics and Engineering, 199, 2010, 557-569. https://doi.org/10.1016/j.cma.2009.10.011