ASEE 2022 ANNUAL CONFERENCE
Excellence Through Diversity
MINNEAPOLIS, MINNESOTA, JUNE 26TH-29TH, 2022 ASEE

Paper ID #36428

Using Topology Optimization in an Undergraduate Classroom Setting

Subodh Subedi

Subodh C. Subedi is a PhD candidate at the Department of Mechanical Engineering at University of Wisconsin-Madison. He is currently working towards his PhD on design for metal additive manufacturing. During his graduate studies, he has worked as a Teaching Assistant (TA) for courses such as Machine Component design, Computer Aided Engineering, and Design Optimization. He is passionate about teaching and has been mentoring undergraduate students in Capstone projects. Apart from graduate studies, he has been actively involved in helping undergraduate student teams for multiple SAE, ASME competitions. Subodh has conducted workshop for high-school students encouraging them to take up engineering. He is regularly involved in multiple outreach events such as state science fairs and expos, sharing his passion for engineering and science. Mr. Subedi has worked as a mechanical engineer in design, manufacturing, installation, testing and commissioning of power projects. He holds a B.Tech in Mechanical Engineering from Motilal Nehru National Institute of Technology, India, M.S. in Mechanical Engineering from University of North Dakota and a M.S. in Mechanical Engineering from University of Wisconsin-Madison.

Krishnan Suresh

Using Topology Optimization in an Undergraduate Classroom Setting

Abstract

Technological advances have significantly reduced lead times in product design. One such advancement is topology optimization (TO) which generates optimal designs to meet specific product specifications. TO is rapidly being adopted by the industry as many commercial computer-aided-design (CAD) platforms now provide in-built modules for TO. This necessitates training of engineering workforce.

In this paper, we discuss the results of a study carried out to quantify the impact of introducing TO to junior undergraduate mechanical engineering students. In this study, students were asked to minimize the weight of a structure by removing material, through trial-and-error, while constantly verifying its performance using finite element analysis (FEA). The students were then asked to optimize the same structure, this time using topology optimization. Results from both approaches were compared for lead time and performance. The trial-and-error approach was significantly worse both in lead time, and design performance, compared to the TO-driven approach. Finally, a course project that involved minimizing the weight of a complex structural component was assigned. Students were able to generate unique designs based on different simulation parameters and constraints chosen during TO.

Thus, a state-of-art design tool was gradually introduced to underclassmen, through lecture, lab exercises and course projects. This study shows that TO can indeed be deployed in a class-room setting to help better prepare the students as they enter the workforce.

1 Introduction

Innovation in product design technologies has made it easier for the engineers to solve complex engineering problems. Use of state-of-art computer-aided design (CAD) tools in the industry is in greater demand due to its impact on reducing product lead times. Consequently, CAD tools have now become an integral part of undergraduate mechanical engineering curriculum. Students can now learn to model, design, analyze and fabricate objects with multitude of tools within a semester course. With the increased interest in industry, updates in these tools with advanced design capabilities are being rolled out every year. There is a greater need to incorporate introductory level training of such tools to better prepare students as they enter industry as engineers.

Topology optimization (TO) [1], [2] is one such techniques that has rapidly evolved from an exciting research field to a powerful tool with applications in numerous industries ranging from automotive [3], [4], aerospace [5], [6], civil engineering [7], [8], thermo-fluids [9], [10] to biomedical [11], [12]. TO generates organic models with optimal material distribution within a design domain, under a given set of loading and restraints. Its ability to provide an initial close-to-optimal structure makes it a very useful tool in digital design and manufacturing. The objective in TO is to find the optimal geometry, within a given design space, that minimizes a specific objective, while satisfying certain constraints. Typical objectives include volume fraction, compliance, etc., while typical constraints include stress, buckling, manufacturing processes, etc.

A typical TO problem is illustrated in Figure 1a, where the left face is fixed, while a downward load is applied on the right face. A symmetry constraint about the XZ-plane is also applied. The beam is then optimized to minimize compliance subjected to a desired volume fraction of 50%. The resulting topology is illustrated in Figure 1b.

(a) *Cantilever beam problem.*

(b) *Optimized beam for 50% volume fraction.*

Figure 1: *A typical topology optimization problem.*

Other topologies of the beam that lie on the *Pareto* curve for various volume fractions are shown in Figure 2.

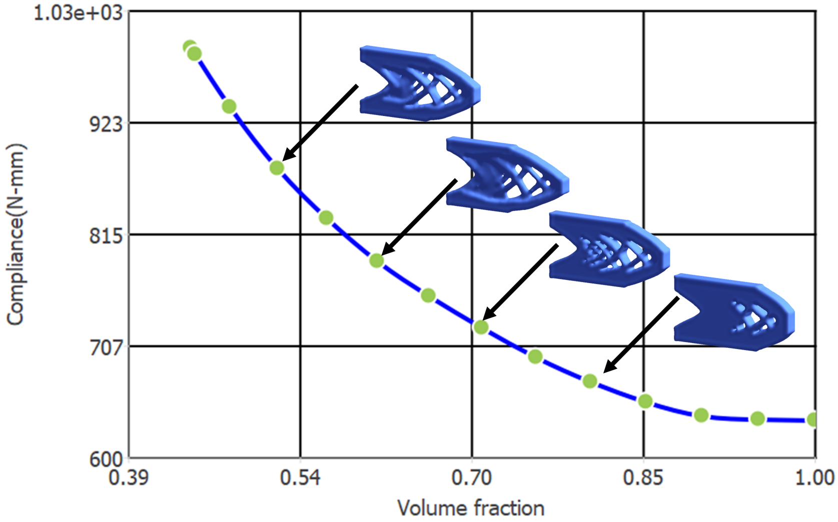


Figure 2: *Pareto optimal curve and Pareto optimal topologies.*

The ease with which one can obtain such optimal designs makes TO a very powerful tool. Most commercial computer-aided-design (CAD) tools today have integrated TO modules. This necessitates the training of engineering workforce to use such powerful tools. This paper presents one such initiative to train undergraduate students in TO, and summarizes the efficacy of incorporating TO as a design tool. Junior undergraduate mechanical engineering students were given the tasks of creating optimal designs, with and without the use of TO software. Section 2 discusses context of this study along with a systematic approach of introducing topology optimization to the students. Quantitative results from the study are also discussed. Finally, conclusion are drawn in Section 3.

2 Methodology

2.1 Context

Undergraduate students enrolled in 'Geometric Modeling for Engineering Applications' (ME 331) in their junior year, were the primary target of this study. The students were already familiar with modeling and basic finite element analysis in SOLIDWORKS [13], a CAD software, from their freshmen and sophomore years. The following are the course objectives for ME 331:

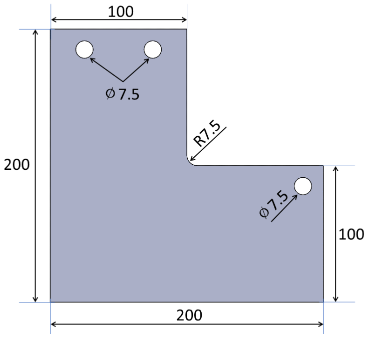
- Advanced CAD Modeling
- Computer Aided Analysis and Optimization
- Computer Aided Manufacturing

The students were first introduced to the concepts of posing valid structural problems, and using finite element analysis (FEA) to solve such problems. Once they were comfortable with FEA, design optimization problems were posed. Students first undertook the painstaking trial-and-error approach to design optimization. This motivated the need for automated topology optimization. Sample problems on topology optimization were introduced through lab exercises. Then, the students were asked to repeat the design optimization problem, using a TO software. The differences in performance and lead time between the two methods were compared. Finally, a course project was assigned that required all the concepts introduced in the course.

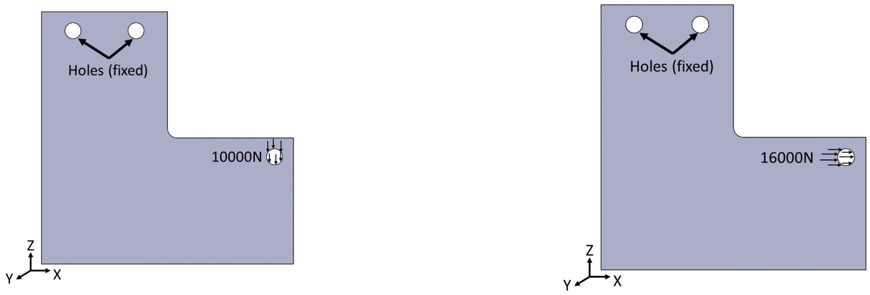
2.2 Manual Design Optimization

The students were tasked with a structural design optimization problem. Specifically, a multi-load optimization problem involving an L-bracket (see Figure 3a) was assigned. The L-bracket (material AIS 310 SS) is subjected to two different load cases/scenarios: (1) a vertical download load of 10,000N on one of the holes as shown in Figure 3b, and (2) a horizontal load of 16,000N on the same hole as shown in Figure 3c. The two holes close to top edge are restrained along all directions. The students were asked to *manually* remove as much material as possible, subject to several constraints: (1) maximum allowable von-Mises stress of 500 MPa, (2) minimum feature size of 5 mm, and (3) manufacturing constraint of extrude along Y-direction.

The students posed and solved two FEAs corresponding to the two load scenarios. Then, based on intuition, they manually removed material from regions with low von-Mises stress (under both loads). Once a new design was obtained, the two FEAs were again carried out. This iterative process was repeated until no further material could be removed. Some of the final designs are shown in Figure 4a. Note that the multi-load scenario makes the trial-and-error process quite challenging. The histogram in Figure 4b shows the distribution of final volume fraction of the brackets achieved by the group of 70 students. The students were able to remove close to 44% material on the aver-



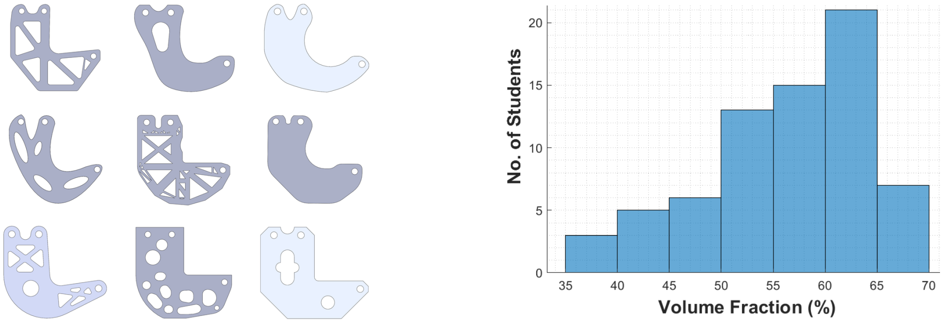
(a) *Detail drawing for L-bracket*



(b) *Load Case 1*

(c) *Load Case 2*

Figure 3: *A multi-load TO problem involving an L-bracket.*



(a) *Results of manual topology optimization for multi-load L-Bracket*

(b) *Histogram of final part volume fractions from manual TO.*

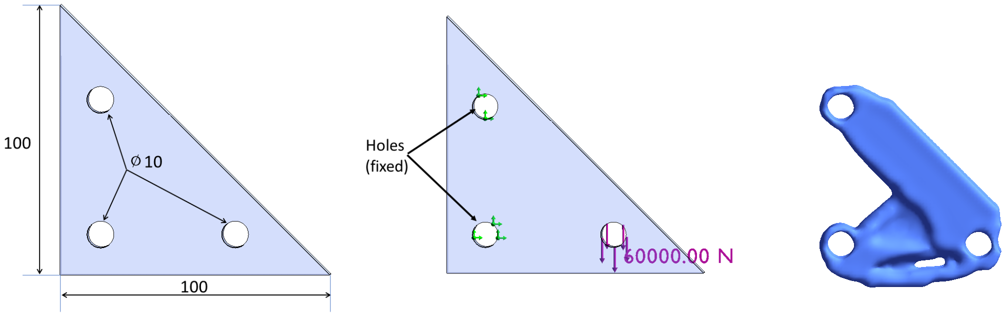
Figure 4: *Results of manual TO.*

age, using 5 to 10 iterations, in about 5 hours.

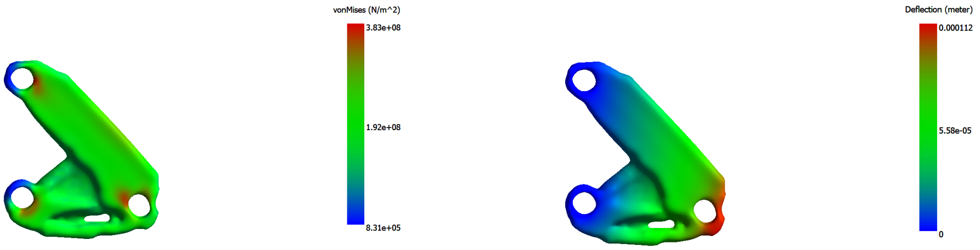
2.3 Automated Topology Optimization

Once the students completed manual design optimization, they were introduced to ParetoWorks [14–16], a SOLIDWORKS add-in for topology optimization. It is tightly integrated with SOLIDWORKS, making it easy to switch between design and optimization. It uses a fast solver for rapid structural FEA. Various physical constraints such as stress, buckling, etc, can be imposed, along with design and manufacturing constraints such as minimum feature size, symmetry, extrude etc.

As an introduction to ParetoWorks, a three hole bracket optimization problem, shown in Figure 5a, was assigned; all dimensions are in mm, and the bracket thickness is 20mm. The two holes close to the left edge are restrained while a vertical load of 60,000N is applied on the third hole. The material is alloy steel, with yield strength of 5 x 10^8 Pa. The objective was to minimize structural compliance, while removing 50% material. The TO problem was solved using ParetoWorks, and the optimized topology is shown in Figure 5c. The stress and displacement plots are presented in Figure 5d and 5e respectively.



(a) *Design domain.* (b) *Loading of bracket.* (c) *Optimized design.*



(d) *Stress plot.* (e) *Displacement plot.*

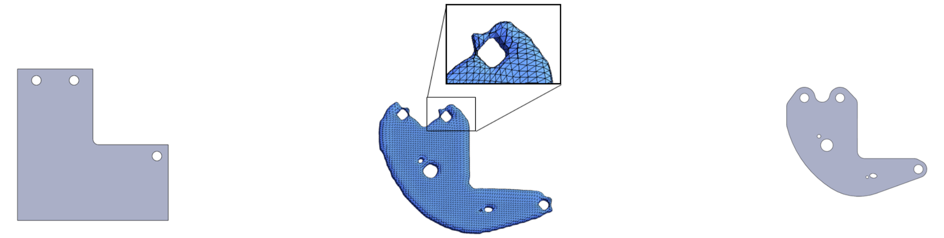
Figure 5: *Topology optimization of the three hole bracket.*

2.4 L-Bracket Problem

Once the students were comfortable with ParetoWorks, the multi-load L-bracket design optimization problem was re-assigned, and the students were asked to solve this using ParetoWorks. Students could use various simulation parameters (ex: mesh size) and design constraints (minimum feature size, symmetry, extrude constraint, etc.) to explore various optimal designs. However, since the software generated triangulated models (see Figure 6b), students had to manually recreate the CAD model after optimization (see Figure 6c), and verify the final design using FEA. (Automated post-processing of TO designs is an active area of research; see [17] for a review.) Despite this manual step, the entire design optimization was completed by most students in less than 2 hours.

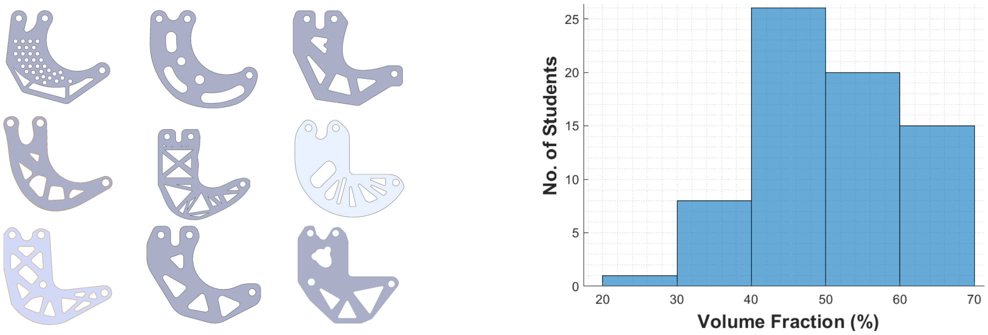
Representative designs created by the students are shown in Figure 7a, while the histogram of final volume fractions is presented in Figure 7b.

A comparison of manual design optimization vs. automated TO is shown in Figure 8. As one can observe, TO significantly improved the performance of the designs, while reducing lead time. The blue box indicates the upper and lower quartiles of the data. The median volume fraction for the L-Bracket designs went down to 49% with automated TO from 57% with manual TO. More



(a) *Initial design.* (b) *Topology optimized design.* (c) *CAD reconstructed design*

Figure 6: *Challenges of TO designs.*



(a) *Results of automated topology optimization for multi-load L-Bracket* (b) *Histogram of final part volume fractions from automated TO.*

Figure 7: *Results of automated TO.*

students were able to generate better designs using less time compared to the manual process.

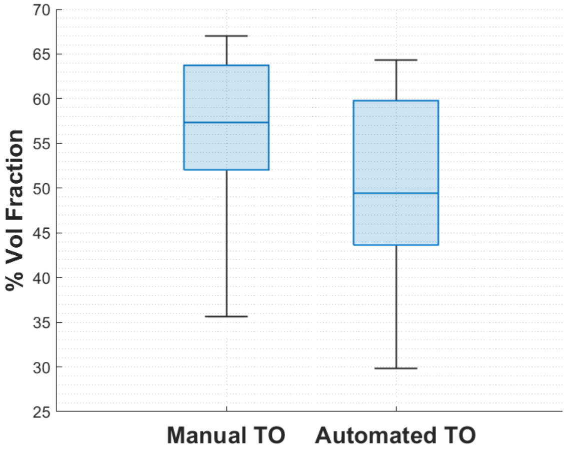
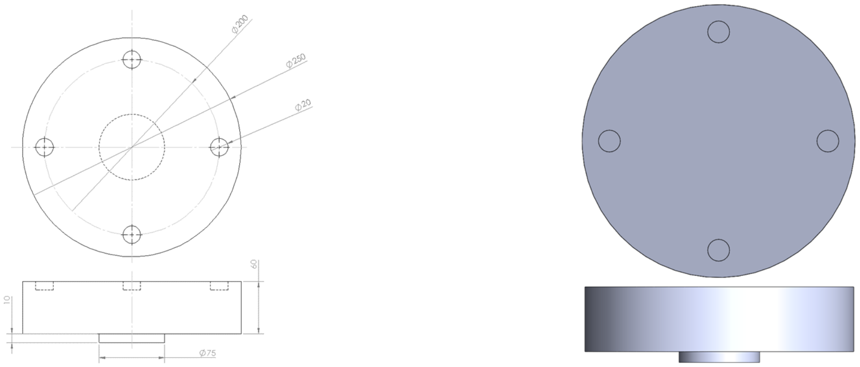


Figure 8: *Comparison of manual vs. automated design optimizaton.*

2.5 Drone Frame Optimization

The students were then assigned a drone frame design optimization problem (see Figure 9) as the final project. The bottom face was fixed and upward force of 4000N was applied on each of the four rotors. The objective was to minimize material usage, without exceeding a stress of 28 MPa.



(a) *Design domain details*

(b) *Initial Design*

Figure 9: *Drone frame.*

Once again, students used ParetoWorks to obtain various designs, based on their choice of simulation and design parameters. Representative designs are shown in Figure 10. Despite using the same TO software, the final designs show that human engineers can interpret these results differently to propose creative solutions.

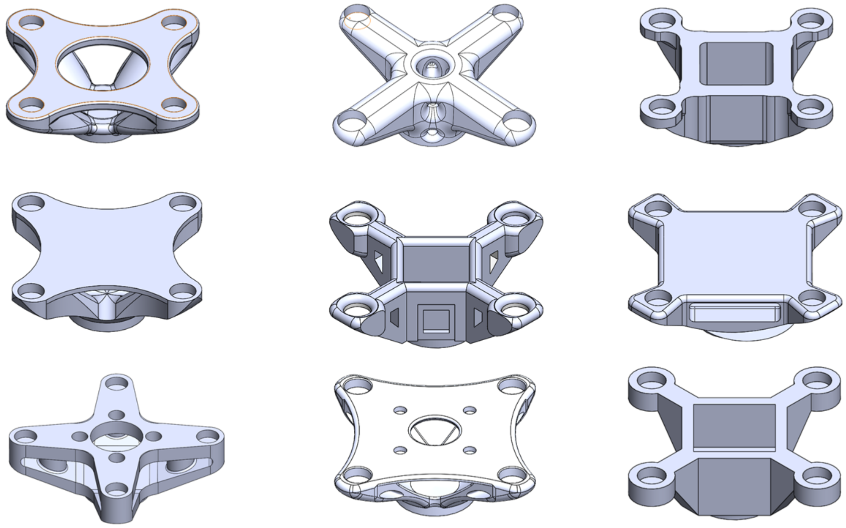


Figure 10: *Optimal drone frames.*

3 Conclusion

The above study showed successful integration of topology optimization, a state-of-art design tool, into the existing undergraduate curriculum. Students were introduced to advanced design tools through project based exercises involving real world scenarios, thereby fulfilling the course objectives on Computer Aided Analysis and Optimization. The learning experience was enhanced with gradual increase in complexity of design optimization problems. Comparative results between manual design optimization and TO indicates significant reduction in material usage, as well as design lead times, using TO. It was also observed that providing students with various simulation options yielded a variety of solutions. The course evaluation survey at the end of semester had very impressive reviews of the course, one of them being ”Lab time was very beneficial. I’ve learned and practiced many skills that I feel like I can take into industry.” In summary, we conclude that a hands-on training of undergraduate students in using advanced design tools such as TO is both doable and rewarding.

4 Acknowledgement

The authors would like to thank the support of National Science Foundation through grant CMMI 1561899.

5 Conflict of Interest

The authors declare that they have no conflict of interest.

References

[1] M. P. Bendsoe and O. Sigmund, “Topology optimization: Theory, methods and applications,” 2003.

[2] O. Sigmund and K. Maute, “Topology optimization approaches,” *Structural and Multidisciplinary Optimization*, vol. 48, no. 6, pp. 1031–1055, 2013.

[3] C. Li, I. Y. Kim, and J. Jeswiet, “Conceptual and detailed design of an automotive engine cradle by using topology, shape, and size optimization,” *Structural and Multidisciplinary Optimization*, vol. 51, no. 2, pp. 547–564, 2015.

[4] C.-H. Chuang, S. Chen, R.-J. Yang, and P. Vogiatzis, “Topology optimization with additive manufacturing consideration for vehicle load path development,” *International Journal for Numerical Methods in Engineering*, vol. 113, no. 8, pp. 1434–1445, 2018.

[5] P. D. Dunning, B. K. Stanford, and H. A. Kim, “Coupled aerostructural topology optimization using a level set method for 3d aircraft wings,” *Structural and Multidisciplinary Optimization*, vol. 51, no. 5, pp. 1113–1132, 2015.

[6] D. Walker and D. Liu, “Topology optimization of an aircraft wing,” in *56th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, 2015, p. 0976.

[7] M. Kociecki and H. Adeli, “Shape optimization of free-form steel space-frame roof structures with complex geometries using evolutionary computing,” *Engineering Applications of Artificial Intelligence*, vol. 38, pp. 168–182, 2015.

[8] Z. H. Zuo, X. Huang, T. Black, P. Felicetti *et al.*, “Application of topological optimisation technology to bridge design,” *Structural Engineering International*, vol. 24, no. 2, pp. 185–191, 2014.

[9] J. Alexandersen and C. S. Andreasen, “A review of topology optimisation for fluid-based problems,” *Fluids*, vol. 5, no. 1, p. 29, 2020.

[10] D. S. Makhija and P. S. Beran, "Concurrent shape and topology optimization for steady conjugate heat transfer," *Structural and Multidisciplinary Optimization*, vol. 59, no. 3, pp. 919–940, 2019.

[11] A. Sutradhar, J. Park, D. Carrau, T. H. Nguyen, M. J. Miller, and G. H. Paulino, "Designing patient-specific 3d printed craniofacial implants using a novel topology optimization method," *Medical & biological engineering & computing*, vol. 54, no. 7, pp. 1123–1135, 2016.

[12] J. Park, A. Sutradhar, J. J. Shah, and G. H. Paulino, "Design of complex bone internal structure using topology optimization with perimeter control," *Computers in biology and medicine*, vol. 94, pp. 74–84, 2018.

[13] D. Systèmes, "Solidworks," http://www.solidworks.com, May 2021.

[14] K. Suresh, "Efficient generation of large-scale pareto-optimal topologies," *Structural and Multidisciplinary Optimization*, vol. 47, no. 1, pp. 49–61, 2013.

[15] ——, "A 199-line matlab code for pareto-optimal tracing in topology optimization," *Structural and Multidisciplinary Optimization*, vol. 42, no. 5, pp. 665–679, 2010.

[16] A. M. Mirzendehdel and K. Suresh, *A Hands-On Introduction to Topology Optimization*, 1st ed. Amazon Kindle Desktop Publishing (KDP), 2017.

[17] S. C. Subedi, C. S. Verma, and K. Suresh, "A review of methods for the geometric post-processing of topology optimized models," *Journal of Computing and Information Science in Engineering*, vol. 20, no. 6, p. 060801, 2020.