Using topology optimization in an undergraduate class-room setting

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Abstract: Technological advances have significantly reduced lead times in product design. One of such advancement is topology optimization (TO), which generates optimal designs to meet specific product specifications. TO is rapidly being adapted by the industry as many commercial CAD platforms 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 topology optimization to junior and senior undergraduate mechanical engineering students. In this study, basic structural finite element analysis (FEA) was first introduced to the students. Structural analysis problems that entailed FEA were then assigned as lab exercises. These exercises formed the basis for introducing design optimization techniques to the class. Students were then asked to minimize the weight of a structure by removing material, through trial-and-error, while constantly verifying its performance using 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 exhibited higher spread both in lead time, and design performance, compared to the TO-driven approach. Although, the TO results needed geometric post-processing, the total time was significantly reduced. Finally, a course project that involved minimizing the weight of a complex structural component subjected to multiple performance and manufacturing requirements was assigned. Students were able to generate unique designs based on different simulation parameters chosen during topology optimization.

Thus, a state-of-art design tool was gradually introduced to underclassmen, though 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

Topology optimization (TO) [1–3] has rapidly transformed from an exciting research field to a powerful tool with applications in numerous industries ranging from automotive [4–7], aerospace [8–12], construction [13–15], thermofluids [16–18] to biomedical [19–22]. TO generates organic models with optimum material distribution within a design domain under the given loading and boundary conditions. Its ability to provide an initial guess for a structure topology under minimum time and cost makes it a very useful tool in digital design and manufacturing.

Various TO strategies, based on their underlying formulations, are well established today and have been widely used to demonstrate their merits. They can primarily be categorized to four groups (a) Density methods [3, 23–25], (b) Level-set methods [26–28], Topological Sensitivity methods [29–31], and (d) Evolutionary Methods [32–34]. The underlying mathematical formulations for each of these methods make them uniquely suitable for wider ranges of problems. The objective in TO is to find the optimal topology, within the given design space, that minimizes a specific objective and satisfies certain constraints. Typical objectives include volume fraction, compliance, etc., while typical constraints include stress, buckling, manufacturing processes, etc. The objectives and constraints can be interchanged.

A typical topology optimization problem for cantilever beam is shown in Figure 1a. The left face is fixed while a vertical download load is applied on the right face. A symmetry constraint about XZ-plane has also

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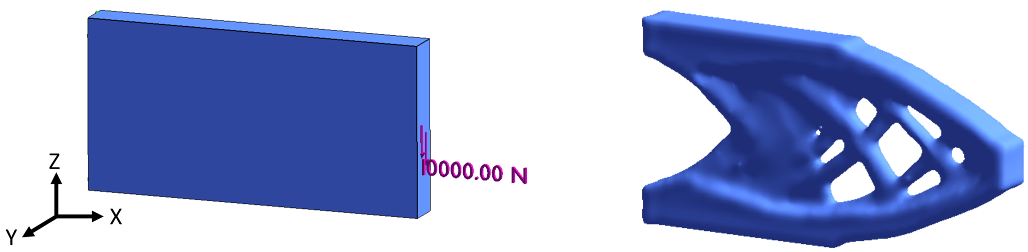
been applied. The beam is then optimized for minimum compliance subjected to a volume fraction of 50%. The results of TO is shown in Figure 1b. One of the advantages of TO is the ability to generate topologies as per the user requirement for the objectives and constraints. A *Pareto* curve for the variation in compliance with part volume fraction is shown in Figure 2, which gives different sets of part topologies based on user requirements for material volume fraction.



(a) *Cantilever beam problem* (b) *TO beam for 50% volume fraction*

Figure 1: *A typical topology Optimization problem*

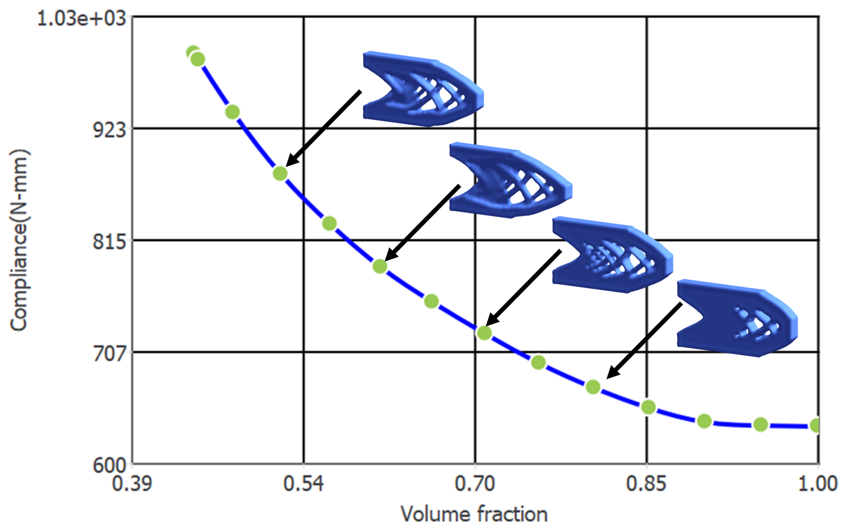


Figure 2: *Pareto Optimal Curve*

The ease of solving complex problems with multiple objectives and multiple constraints makes TO a powerful tool. Most of the commercially available CAD tools have integrated one or more methods of TO into their design modules. This necesitates the training of engineering workforce to work on real world challenges. This paper presents one such initiatives to train undergraduate students in this state-of-art design too. We studied the efficacy of incorporating topology optimization as a design tool, in an undergraduate classroom setting. Specifically, undergraduate mechanical engineering students at the University of Wisconsin, Madison were given the tasks of creating optimal designs, with and without the use of TO software. Section 2 discusses the context of this study. A systematic approach for introducing TO to the students is discussed through problem sets in Section 3. Results and discussions for different studies are presented in the section. Finally, conclusion based on these studies are presented in Section 4.

2 Context

To study the effectiveness of using topology optimization in creating better designs, undergraduate students enrolled in 'Goemetric Modeling for Engineering Applications' course were introduced to structural finite element analysis in lectures. The basic concepts of design domain, mesh, loads, restraints and post-processing were taught through examples. Topology optimization was then introduced to the students using a SolidWorks plugin of Pareto, a commercial TO software developed at the author's lab at the University of Wisconsin-Madison. The student enrolled in the course were already familiarized with CAD modeling tool in their freshmen and sophomore years.

3 Methodology

As the students got familiar using structural FEA modules in SolidWorks, topology optimization was introduced through lab exercises. Students were given different target values for each exercises based on the functionality of the part and its material. The goal of these tasks were to optimize the topology of the part based on the given loading conditions to meet target volume fraction and satisfy functional requirements. Three different problem sets were provided to the students with increasing levels of complexities in designs as discussed below.

3.1 Problem 1: Bicycle Crank

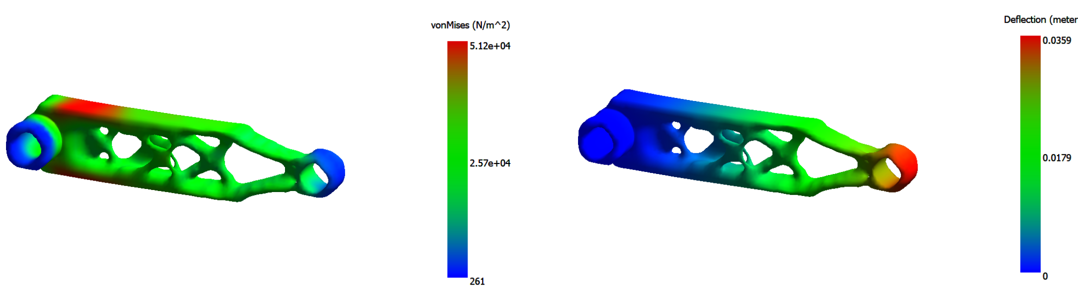
A bicycle crank model was provided to the students along with the loading and boundary conditions as shown in Figure 3. The hole on the left is fixed while a vertical upwards load of 1000N is applied on the right hole. The problem details are listed below.

- Material: Alloy Steel
- Yield Strength : 5e8 Pa
- Objective: Minimize compliance
- Target Volume Fraction: 0.5

Topology optimized design by one of students for the bicycle crank is shown in Figure 3b. The wireframe shows the boundaries of initial design. Results for stress and displacement distribution in the topology optimized designs are presented in Figure 4. The stress is well under the yield limit.

(a) *Initial Design* (b) *TO Design with 50% volume fraction*

Figure 3: *Topology Optimization of bicycle crank*

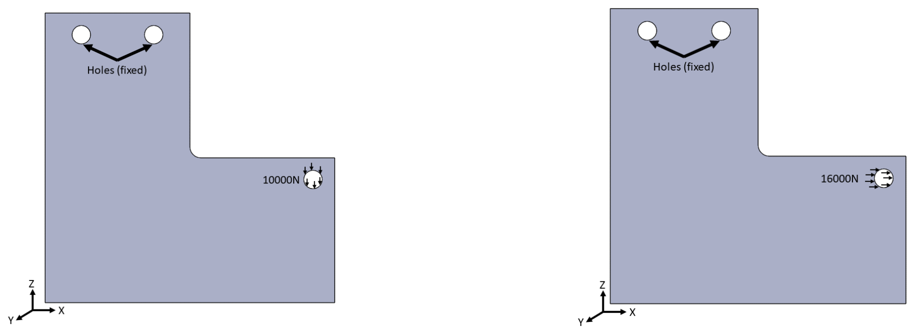


(a) *Stress Plot* (b) *Deformation Plot*

Figure 4: *Results of Topology Optimization of bicycle crank*

3.2 Problem 2: L-Bracket

A multi-load problem is formulated for TO, where, any part undergoes different loading conditions subjected to the same restraints at different instances of time. The L-bracket is subjected to two different load cases, (1) a vertical download load of 10,000N on one of the holes as shown in Figure 5a, and (2) a horizontal load of 16,000N on the same hole as shown in Figure 5b. The two holes close to top edge are restrained for zero deformation along all directions.



(a) *Load Case 1* (b) *Load Case 2*

Figure 5: *A multi-load TO problem for L-bracket*

The problem can be summarized as,

- Material: AIS 310 SS
- Maximum allowable von-Mises Stress: 500 MPa
- Target Volume Fraction: 0.5
- Minimum feature size: 5 mm
- Manufacturing constraint: Forging along Y-direction

Students were tasked with two different approaches to obtain an optimal design of the L-bracket as discussed below.

3.2.1 Approach 1: Manual Topology Optimization

The objective of the first task was to manually remove material from areas with lower von-Mises stress, until the part yields. Based on the approximated shape of areas with lower stress, features were cut-out from the part. Once a cutout is made in the part to remove material, two finite element runs were carried out to check their conformity to design requirements for allowable stress. This iterative process of trial-an-error continues until a minimum material volume fraction design is obtained that does not yield under both the loading conditions. This is a labor-intensive approach to solving the problem that involves lot of trial-and-error iterations. It takes significant amount of time and requires an experienced user to come up with a final solution to the problem. Some of the representative designs from the manual topology optimization are shown in Figure 6.

The histogram in Figure 7 shown the distribution of minimum volume fraction achieved by the group of 71 students from different lab sections. The students were able to remove close to 44% material at average, from over 5 to 10 iterations of designs to satisfy the yield criteria. The exercise took over 5 hours to complete for each of the students.

3.2.2 Approach 2: Automated Topology Optimization

The same group of students were asked to use ParetoWorks, a SolidWorks plugin, for topology optimization of the multi-load L-Bracket problem. One of the biggest challenges of topology optimization is the requirement of geometric post-processing of the results for downstream applications. The plugin uses a .STL file and hexagonal non-conformal mesh to solve FEA. This gives rough edges and surfaces for the optimized

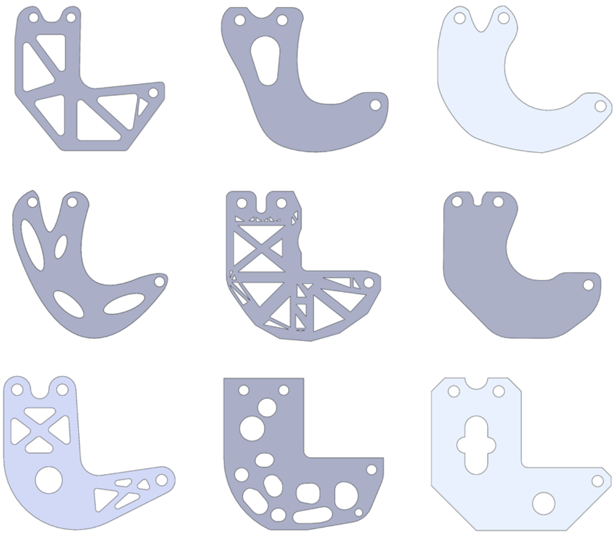


Figure 6: *Results of manual topology optimization for multi-load L-Bracket*

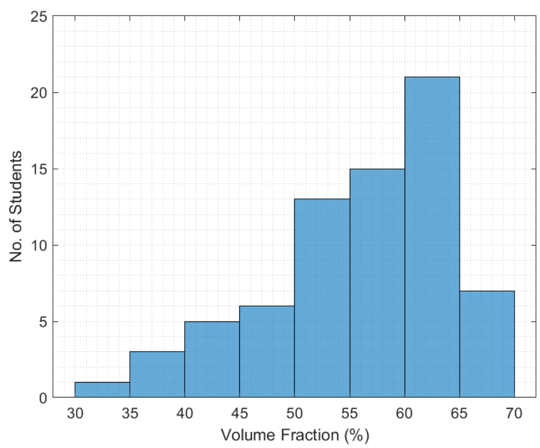
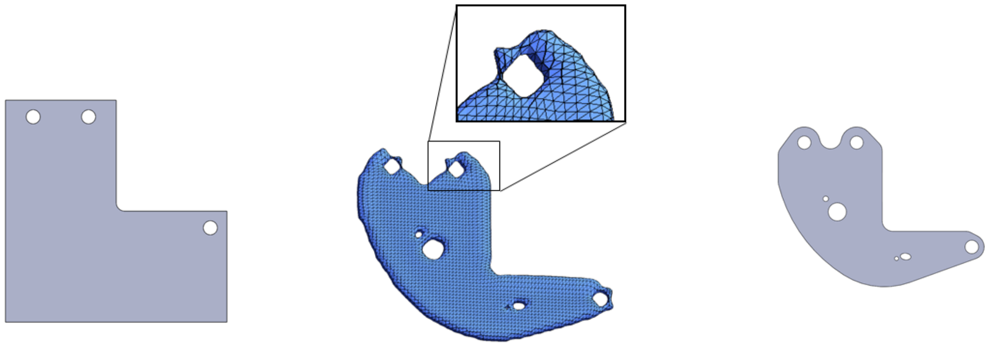


Figure 7: *Histogram of final part volume fractions*

geometry, which is also represented by set of triangles for .STL file. As seen in Figure 8b, some of the features (sharp edges, circular holes, flat surfaces, etc) get lost due to non-conformal mesh during topology optimization. Thus, the TO design requires post-processing to recover such features as well as other downstream applications. A full review of existing approaches on post-processing of TO designs can be found on Subedi et.al [35]. One of the easiest ways for reconstruction of CAD geometry from TO designs is to trace the boundaries to form a closed sketch. These sketches can then be extruded to construct a 3D geometry as shown in Figure 8c. Students followed the idea of tracing the boundaries of the TO design to reconstruct a corresponding CAD model of L-bracket. Representative designs from the same set of students for the CAD reconstructed TO models are shown in Figure 9. The TO optimized results acted as initial guess for the students to come up with their final designs, which is evident in the representative designs shown in Figure 9. These designs were obtained within a single lab session of 2 hours. Also, the spread in volume fraction acheived was much lesser than that for the earlier approach as seen in the histogram in Figure 10.

A comparison of results from both approaches is shown in Figure 11. For the trial-and-error approach of using manual topology optimization, the average volume fractions acheived was 56.22% while it was 50.18% for the second approach of using the TO plugin. Thus, using tool for topology optimization tool significantly reduced the design lead times as well as the spread in results for final part volumes.



(a) *Initial Design* (b) *Topology Optimized Design* (c) *CAD Reconstructed TO Design*

Figure 8: *A multi-load TO problem for L-bracket*

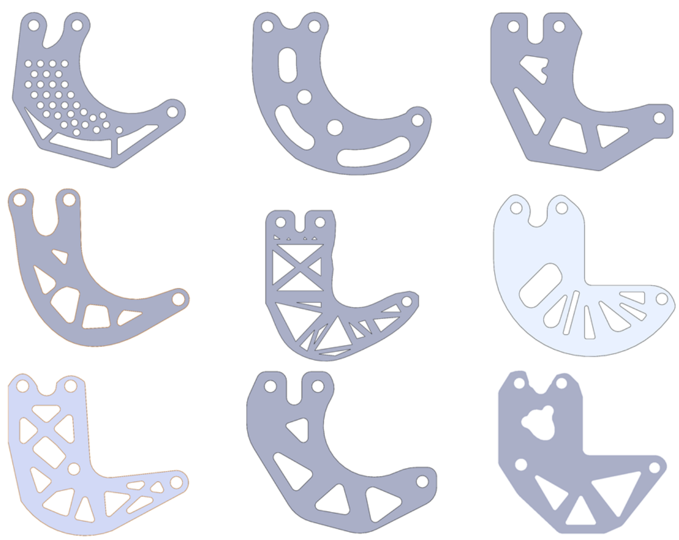


Figure 9: *Results of manual topology optimization for multi-load L-Bracket*

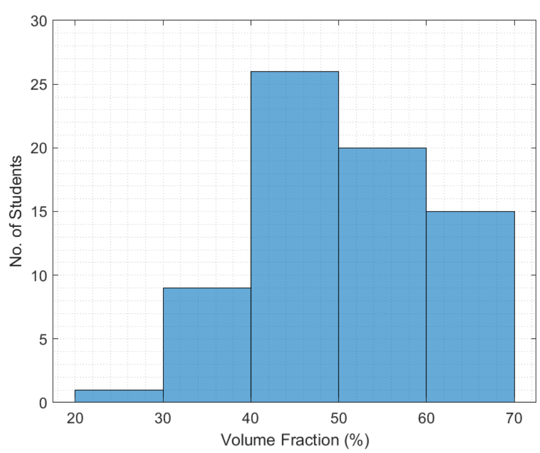


Figure 10: *Histogram of final part volume fractions using Pareto*

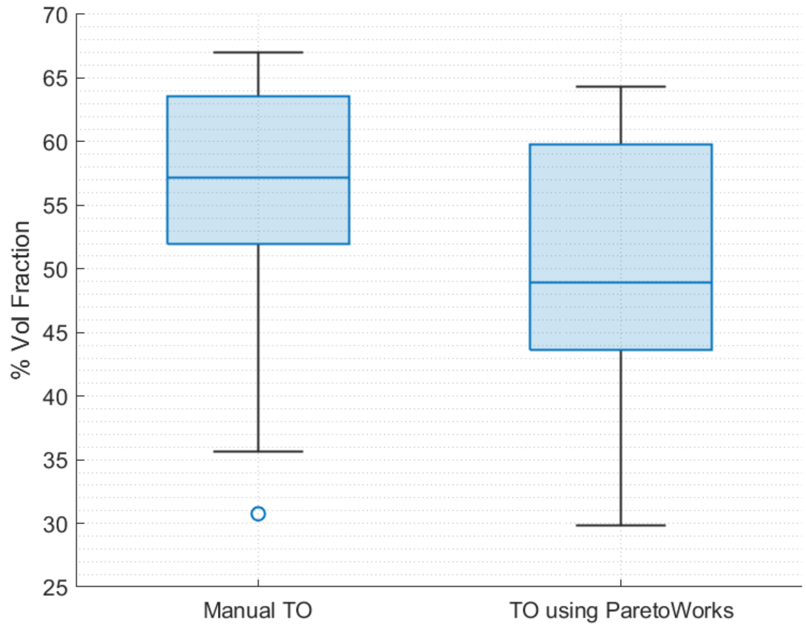


Figure 11: *Histogram of final part volume fractions*

3.3 Problem 3: Drone Frame

The students were then assigned a problem on drone frame optimization as the course project. CAD model shown in Figure 12, for the initial design space was provided. The loading conditions were meant to simulate the forces that a Drone's frame incurs during takeoff from the ground with full load. The positions of motors that power the wings were specified using pockets and the attachment for payload was specified by adding a cylindrical feature at the bottom. The bottom face was fixed and upward force of 4000N was applied on each of the rotors. Students were asked to optimize the topology of the drone frame. This is a multiple load problem where different loads act at the same time. The objective was to minimize the material usage so students were asked to report the minimum material volume fraction they could achieve after topology optimization and CAD reconstruction. The final CAD model also needed to be validated to conform to the yeilding requirements.

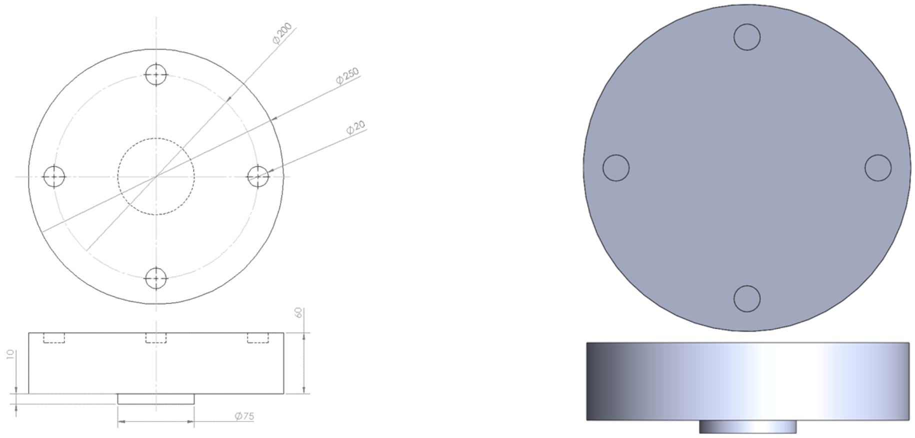
The problem details are,

- Material: ABS
- Maximum allowable von-Mises Stress: 42 MPa
- Factor of safety: 1.5 mm
- Constraint: Any constraint

Students used ParetoWorks to obtain the topology optimized model based on their choice of manufacturing/symmetry constraints. Using the optimized topology, they used different material removal features to carve material out of the initial design of drone frame. Representative images of validated CAD models of drone frames are shown in Figure 13. The results show wide variety of possible designs generated by students using different sets of constraints during optimization.

4 Conclusion

The above study showed the successful integration of a state-of-art research tool into undergradute curriculum. Student learning experience was enhanced with gradual increase in the challenges from single load



(a) *Design domain details*

(b) *Initial Design*

Figure 12: *Drone Frame Details*

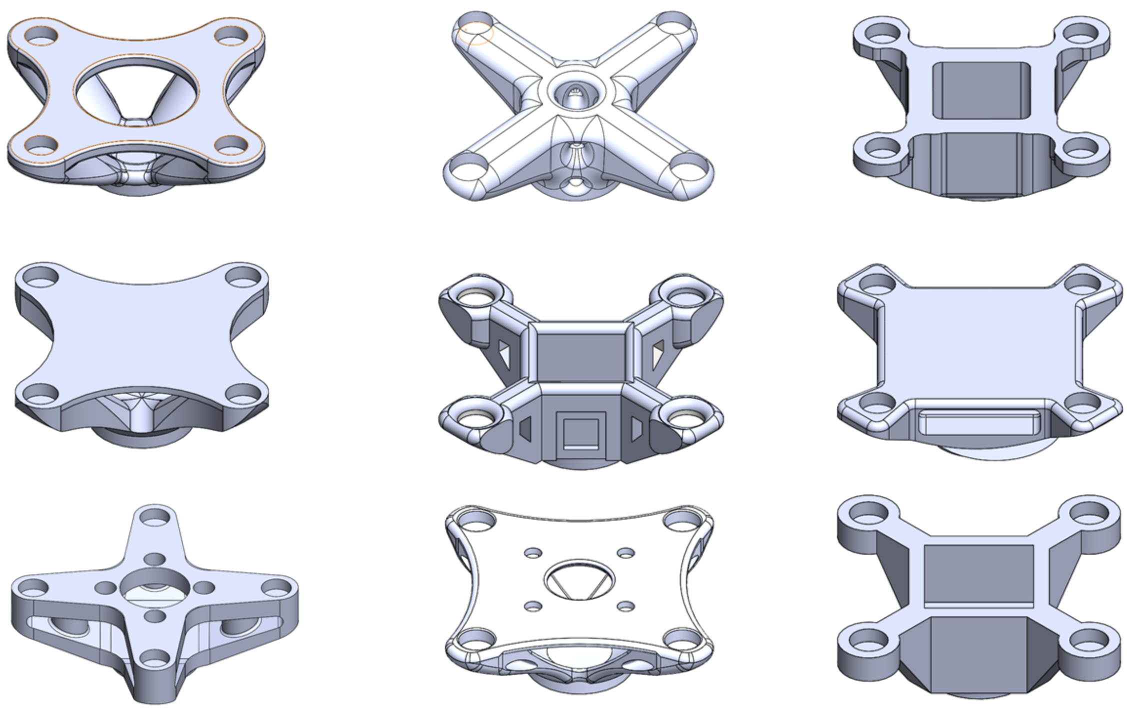


Figure 13: *CAD models for drone frames*

to multi-load and multiple loading scenarios. Comparative results for the trial-and-error approach with TO using Pareto indicates significant reduction in material usage as well as design lead times. Also, the spread on the final design volume fractions were higher for the manual approach compared to using Pareto. Providing students with freedom to choose constraints yielded in variety of solutions for the same problem as seen through the drone frame optimization problem. Introduction and hands-on training of undergraduate students in advanced design tools like TO will equip them with skillsets that will make them stand out as they enter the workforce after graduation.

5 Acknowledgement

6 Conflict of Interest

References

[1] Martin P Bendsøe. *Topology optimization*. Springer, 2009.

[2] Martin P Bendsoe and Ole Sigmund. Topology optimization: Theory, methods and applications, 2003.

[3] Ole Sigmund and Kurt Maute. Topology optimization approaches. *Structural and Multidisciplinary Optimization*, 48(6):1031–1055, 2013.

[4] Liangsheng Wang, Prodyot K Basu, and Juan Pablo Leiva. Automobile body reinforcement by finite element optimization. *Finite Elements in Analysis and Design*, 40(8):879–893, 2004.

[5] Chao Li, Il Yong Kim, and Jack Jeswiet. Conceptual and detailed design of an automotive engine cradle by using topology, shape, and size optimization. *Structural and Multidisciplinary Optimization*, 51(2):547–564, 2015.

[6] Denghong Xiao, Xiandong Liu, Wenhua Du, Junyuan Wang, and Tian He. Application of topology optimization to design an electric bicycle main frame. *Structural and Multidisciplinary Optimization*, 46(6):913–929, 2012.

[7] Ching-Hung Chuang, Shikui Chen, Ren-Jye Yang, and Panagiotis Vogiatzis. Topology optimization with additive manufacturing consideration for vehicle load path development. *International Journal for Numerical Methods in Engineering*, 113(8):1434–1445, 2018.

[8] Ji-Hong Zhu, Xiao-Jun Gu, Wei-Hong Zhang, and Pierre Beckers. Structural design of aircraft skin stretch-forming die using topology optimization. *Journal of Computational and Applied Mathematics*, 246:278–288, 2013.

[9] Peter D Dunning, Bret K Stanford, and H Alicia Kim. Coupled aerostructural topology optimization using a level set method for 3d aircraft wings. *Structural and Multidisciplinary Optimization*, 51(5):1113–1132, 2015.

[10] David Walker and David Liu. Topology optimization of an aircraft wing. In *56th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, page 0976, 2015.

[11] E Kesseler and W. Vankan. Multidisciplinary design analysis and multi-objective optimisation applied to aircraft wing. *WSEAS Transactions on Systems and Control*, 1, 01 2006.

[12] Juan J Alonso, Patrick LeGresley, and Víctor Pereyra. Aircraft design optimization. *Mathematics and Computers in Simulation*, 79(6):1948–1958, 2009.

[13] Maggie Kociecki and Hojjat Adeli. Shape optimization of free-form steel space-frame roof structures with complex geometries using evolutionary computing. *Engineering Applications of Artificial Intelligence*, 38:168–182, 2015.

[14] B Briseghella, Luigi Fenu, C Lan, E Mazzarolo, and T Zordan. Application of topological optimization to bridge design. *Journal of Bridge Engineering*, 18(8):790–800, 2012.

[15] Zhi Hao Zuo, Xiaodong Huang, Tim Black, Peter Felicetti, et al. Application of topological optimisation technology to bridge design. *Structural Engineering International*, 24(2):185–191, 2014.

[16] Joe Alexandersen and Casper Schousboe Andreasen. A review of topology optimisation for fluid-based problems. *Fluids*, 5(1):29, 2020.

[17] David S Makhija and Philip S Beran. Concurrent shape and topology optimization for steady conjugate heat transfer. *Structural and Multidisciplinary Optimization*, 59(3):919–940, 2019.

[18] Kentaro Yaji, Takayuki Yamada, Masato Yoshino, Toshiro Matsumoto, Kazuhiro Izui, and Shinji Nishiwaki. Topology optimization in thermal-fluid flow using the lattice boltzmann method. *Journal of Computational Physics*, 307:355–377, 2016.

[19] Alok Sutradhar, Jaejong Park, Diana Carrau, Tam H Nguyen, Michael J Miller, and Glaucio H Paulino. Designing patient-specific 3d printed craniofacial implants using a novel topology optimization method. *Medical & biological engineering & computing*, 54(7):1123–1135, 2016.

[20] Pedro G Coelho, Scott J Hollister, Colleen L Flanagan, and Paulo R Fernandes. Bioresorbable scaffolds for bone tissue engineering: optimal design, fabrication, mechanical testing and scale-size effects analysis. *Medical engineering & physics*, 37(3):287–296, 2015.

[21] Xiaojian Wang, Shanqing Xu, Shiwei Zhou, Wei Xu, Martin Leary, Peter Choong, M Qian, Milan Brandt, and Yi Min Xie. Topological design and additive manufacturing of porous metals for bone scaffolds and orthopaedic implants: A review. *Biomaterials*, 83:127–141, 2016.

[22] Jaejong Park, Alok Sutradhar, Jami J Shah, and Glaucio H Paulino. Design of complex bone internal structure using topology optimization with perimeter control. *Computers in biology and medicine*, 94:74–84, 2018.

[23] RJ Yang and CJ Chen. Stress-based topology optimization. *Structural optimization*, 12(2):98–105, 1996.

[24] Erik Andreassen, Anders Clausen, Mattias Schevenels, Boyan S Lazarov, and Ole Sigmund. Efficient topology optimization in matlab using 88 lines of code. *Structural and Multidisciplinary Optimization*, 43(1):1–16, 2011.

[25] Ole Sigmund. A 99 line topology optimization code written in matlab. *Structural and multidisciplinary optimization*, 21(2):120–127, 2001.

[26] Vivien J Challis. A discrete level-set topology optimization code written in matlab. *Structural and multidisciplinary optimization*, 41(3):453–464, 2010.

[27] Nico P van Dijk, Kurt Maute, Matthijs Langelaar, and Fred Van Keulen. Level-set methods for structural topology optimization: a review. *Structural and Multidisciplinary Optimization*, 48(3):437–472, 2013.

[28] Masaki Otomori, Takayuki Yamada, Kazuhiro Izui, and Shinji Nishiwaki. Matlab code for a level set-based topology optimization method using a reaction diffusion equation. *Structural and Multidisciplinary Optimization*, 51(5):1159–1172, 2015.

[29] Jean Céa, Stéphane Garreau, Philippe Guillaume, and Mohamed Masmoudi. The shape and topological optimizations connection. *Computer methods in applied mechanics and engineering*, 188(4):713–726, 2000.

[30] Antonio André Novotny, Raúl A Feijóo, Edgardo Taroco, and Claudio Padra. Topological sensitivity analysis. *Computer methods in applied mechanics and engineering*, 192(7-8):803–829, 2003.

[31] Krishnan Suresh. A 199-line matlab code for pareto-optimal tracing in topology optimization. *Structural and Multidisciplinary Optimization*, 42(5):665–679, 2010.

[32] Xiaodong Huang and YM Xie. Convergent and mesh-independent solutions for the bi-directional evolutionary structural optimization method. *Finite elements in analysis and design*, 43(14):1039–1049, 2007.

[33] XY Yang, YM Xie, GP Steven, and OM Querin. Topology optimization for frequencies using an evolutionary method. *Journal of Structural Engineering*, 125(12):1432–1438, 1999.

[34] Xiaodong Huang and Yi Min Xie. Bi-directional evolutionary topology optimization of continuum structures with one or multiple materials. *Computational Mechanics*, 43(3):393–401, 2009.

[35] Subodh C Subedi, Chaman Singh Verma, and Krishnan Suresh. A review of methods for the geometric post-processing of topology optimized models. *Journal of Computing and Information Science in Engineering*, 20(6):060801, 2020.