

THE POTENTIAL OF LOW COST TOPOLOGY OPTIMIZATION

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ABSTRACT

Topology optimization (TO) is a powerful tool to generate forms for structural parts. Used at the beginning of the design process, it can generally lead to a reduction of iteration loops and an optimization of the weight/stiffness ratio. It has been argued that the application of TO could also be effective in the hands of industrial design. Moreover, TO could help to add plausibility to the theory of technical mechanics and structural concepts in design and engineering education. These benefits are not being utilized by a large share of potential users for mainly two reasons. Firstly, current commercial software involves a great financial invest. Secondly, an effective use of the software requires extensive training, which is the main hindrance against the method's application in conventional engineering education, where no time can be cut from the tight schedules to learn to operate additional software. However, in recent years, a range of rather basic, free TO software has become available on the internet. Starting the discussion if such offers are interesting options for engineering and design education and practice, this paper gives an overview of the functionality of current free TO software. Next, a specific case is studied with one commercial and several free TO programs. The investigation focuses on available functionalities for defining geometry and load cases as well as on the qualitative or quantitative rating of the optimized structures. The question of interest is if the disadvantages of the reduced performance of free software can be compensated by the advantages of saving time and budget and to what extent such freeware can be a feasible alternative to professional FEM-based software, especially in the context of enhancing engineering education and supporting designers.

Keywords: Topology optimization, enhancing engineering education, industrial design

1 INTRODUCTION

TO has already been having a positive influence on the development of especially technical products. The technology of TO has been well established particularly in fields where optimized weight but strong mechanical performance is required. TO is working as a "creating tool" and not as a "correcting tool" like classical FEA software. As a consequence the number of iterations loops in the development of a product (as in VDI 2221 [1]) can be reduced.

Former investigations have shown that TO could also be an effective tool in the hands of industrial designers [2]. The advantage of the already mentioned shorter developmental cycle could be taken or, even if the digital data of the optimized results was not employed directly, the generated geometries could be used as an inspiration for new shapes. This obvious potential is not being used as most of commercial TO-software has grown out of traditional FEM-software. Therefore handling the user interface and interpreting the results of such programs usually requires a basic knowledge of technical mechanics. Especially for designers with little technical background this constitutes a barrier to using TO. Additionally, purchasing commercial software means a great financial invest. The ideal TO-software is therefore free of charge as well as easy and intuitive to operate. For industrial designers it would help to easily generate mechanically feasible products. For engineers, easier and cheaper access to this technology would open up one more possibility for the development of economical products of good structural quality. Additionally, that kind of software could be used in education for designers and engineers to support the comprehension of mechanical relations in a visual way. At RWTH Aachen University, in a master course "Konstruktionslehre II" (Design Methodology) the method of TO is being taught by practical studies using the professional software *Altair Optistruct* with satisfying success. However, a large share of the teaching time is spent on the operation of the software, which

only leaves enough time for one optimization study, a cantilever beam. More diverse case studies within the same overall teaching time are wished for, because they would improve the actual understanding of the method, and finally increase the students' motivation to use and study this technology in their own projects. This research contributes to making TO accessible to a wider range of potential users by giving an overview of currently available free TO-software. The investigation focuses on the handling of the software as well as on the quality of the output. To make results qualitatively and maybe even quantitatively comparable, a specific case was first studied with the commercial TO-software *Altair Optistruct* and then remodelled with several free TO-programs. In this work the term *quantitative* refers to numerical values for e.g. dimensions or stresses whereas *qualitative* illustrates relative data such as coloured scales. To help understand the basics of TO some theoretical background is presented before the software and the case study is presented and discussed.

2 THEORETICAL BACKGROUND OF TOPOLOGY OPTIMIZATION

The aim of structural optimization is to achieve e.g. maximum stiffness or minimum mechanical stresses in a component while limiting usually the volume or mass. Three different categories of structural optimization have been established: sizing, shape and topology optimization. [3]

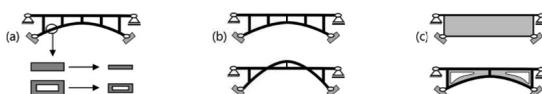


Figure 1. Structural optimization: (a) sizing, (b) shape and (c) topology optimization [4]

In sizing optimization, only the dimensions of the cross-sections are varied to optimize the structure. In shape optimization, the structure is being optimized by shifting particular nodal points without a change in topology. In both categories the topology needs to be fully defined before the optimization process. Consequently, an experienced designer is required for a reasonable starting topology and the quality of the final solution is limited by the quality of the first draft. In TO only the available design space, loads and constraints are met, which can result in new contours and even cavities. Thus TO is the only approach where no experience or knowledge of structural mechanics are needed. [3]

The general approach for TO is the definition of the available design space, non-design space (solids), cavities (voids), a load case and optimization parameters. Material that does not take any loads is supposed to be removed through the optimization process. The remaining material constitutes the ideal structure and is fully utilized at any point. For the optimization, several numerically and heuristic approaches have been developed. [3] This paper concentrates on the SIMP algorithm as it is employed by all presented software apart from BESO2D. SIMP uses an artificial normalized density as design variable. The density is numerically connected with the Young's modulus. Using an FE-solver, iteratively a density between 0 and 1 gets assigned to each element. If the density of an element is 0, it becomes void; being 1 it is solid. To encourage the formation of distinct structures, intermediate values are suppressed using the penalization factor $p > 1$. In post-processing, a threshold called *iso* can usually be set, to regulate which densities are displayed. Alternating voids and solids (checkerboard effect) is being counteracted with different filters. For further information on SIMP see [3]. If a TO is calculated with SIMP, an optimization problem is to be solved. This paper concentrates on the most common optimization problem maximizing the stiffness while keeping a certain volume fraction. For known forces, maximizing the stiffness is equivalent to minimizing the compliance [3]. If several forces are applied but do not work concurrently, they do not compensate each other or add up. Thus more than one load case is required. If the occurrence of the applied forces is not equal, they need to be weighted. The descriptions of all analyzed programs refer to the work flow of a TO in Figure 2.

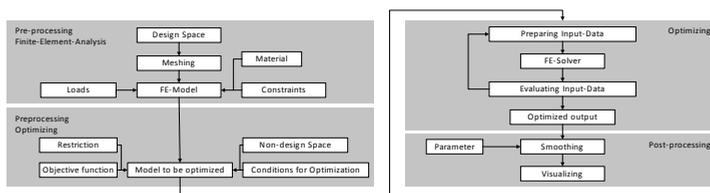


Figure 2. General work flow of topology optimization [5]

3 TO software

3.1 TO with free software

The community *topology-opt* [6] offers a good summary of currently available TO-software, both commercial and free. Besides *Altair Optistruct*, this paper only discusses freeware. All of the free software was developed to ease the access to the technology of TO in particular for educational purposes. The majority is an outcome of university projects. The presented software is classified according to its complexity, beginning with scripts that are solely working without Graphical User Interface (GUI), followed by online software with GUI. Almost none of the online software offers import or export facilities for geometrical data. The last programs introduced require a download but offer more input and output options. All of the presented programs solve the minimum compliance problems with the restriction of a volume fraction. The 2D programs automatically use pixels (cubic) and the 3D programs voxels (hexagon) as finite elements.

A famous example of a script is the 88-line Matlab code developed by the Technical University of Denmark (DTU) which is optimizing a fixed 2D beam-problem [7], [10]. The script provides a good outline of the theory behind TO and is suitable to study the influences of the input parameters. To change the load case the script needs to be modified, which requires programming skills. There is another Matlab script solving a 3D problem [8] and a Python script solving the same 2D problem. The results are displayed as graphic files. *ToPy* [9] is a Python script without GUI importing txt-files in which load case and geometry are defined. The design space, non-design-elements, being either solid or void, and each element and node on which a force or a constraint is applied, need to be defined discretely by writing the information into a txt-file. No multiple load cases, no dead load (self-weight) and no weighting of forces can be applied. For the optimization several filters as well as the penalization factor are to be set. In *ToPy* no post-processing is available. To visualize the vtk-output-files an external reader is required (here: *Paraview*). *ToPy* is quite flexible in defining geometry and load cases compared to the Matlab scripts, but its handling is not intuitive and time consuming.

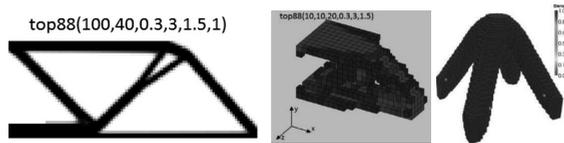


Figure 3. Optimized structures of 88-line Matlab code, 3D Matlab code and ToPy

Three online programs with a GUI were also developed at the DTU [10]. In all of them up to three load cases can be defined. No dead load or weighting of the forces is applicable but the volume fraction is adjustable. *TopOpt App* is a 2D interactive web player or app for hand-held devices which optimizes a given topology in real time. Supports and loads are set and moved via drag and drop. A sensitivity filter is automatically used. The penalization factor is fixed to 3. Three different resolutions are available. The second 2D web player *compliance design* almost has the same functions but is not optimizing in real time. The filter radius and the penalization factor are adjustable within a certain range. The resolution cannot be changed. Apart from graphical output the optimized geometries cannot be exported or saved. In the third web player *3D compliance design* the geometry is not handled using drag and drop but defined by coordinates for the design space, non-design space, cavities, loads and supports. Again the filter radius and penalization factor are adjustable. The resolution is defined by the total number of elements. The optimized 3D geometry is opened in a new window where the iso value can be adjusted. The 3D data is exportable as stl-files. All of the three programs provide a very intuitive and quick way to qualitative TO results.

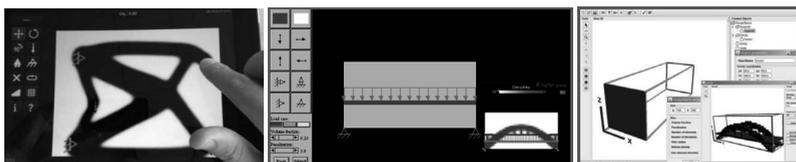


Figure 4. left: TopOpt App, middle: 2D compliance design, right: 3D compliance design

Two different 2D programs which require a download are also a result of university projects. The first one is called *BESO2D* developed at RMIT Melbourne [11], using the BESO algorithm to solve the optimization program. The second program *ForcePAD* is from Lund University in Sweden [12]. Both programs work similarly as the geometry is sketched in a graphical interface as in *Microsoft Paint*. *ForcePAD* also has the ability to import pictures from files or the clipboard. In *BESO2D* cavities and non-design space can be defined, whereas *ForcePAD* only supports cavities. Supports and loads are applied with drag and drop. In *BESO2D*, value and direction of forces are defined by coordinates. In *ForcePAD*, only a value can be entered; the direction is set manually in the GUI. Both programs can only employ one load case and no weighting of forces. Material parameters can be set. A FEA is run before the optimization is started giving quantitative results of stresses and qualitative displacements in *BESO2D* and qualitative results of stresses, displacements and reaction forces at the supports in *ForcePAD*. For both software volume fraction, filter radius and the type of filter can be selected. An iso value can be set for the optimized geometry. As post-processing both programs run a FEA of the optimized structure. The load cases and the geometry can be saved, but no export of the optimized geometries is offered. Both programs are intuitive to handle and offer quick qualitative, partly quantitative optimized 2D results (see Figure 5).

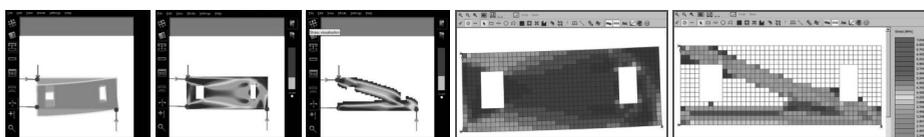


Figure 5. left: *ForcePAD*, right: *BESO2D*

Another free TO software *Topostruct* was developed by the architects and designers K. Sawako and M. Panagiotis offering 2D and 3D TO [13]. The geometry is built out of basic geometries such as cuboids, cylinders and spheres. Supports and loads are also applied by inserting geometrical spaces that become active where they touch the design space. The entire interface is operated using drag and drop. Values and directions of the forces are defined by coordinates. Only one load case is applicable and the forces cannot be weighted. A dead load can be employed but as no material parameters are given it is not clear to the user if the density, the weight or the force needs to be entered. Apart from the initial design space no dimensions for supports, non-design spaces and cavities are given. Thus the modelling is not very precise. For the TO the volume fraction, penalization factor and filter options are to be set. What kind of filter it is and how its parameters influence the TO is not properly explained. After the optimization the iso value can be adjusted. *Topostruct* offers a smoothing option for the optimized structure. Running an FEA before and after the TO determines qualitative stresses, displacements and force distribution. The 3D geometrical data is exportable as dxf-files. *Topostruct* is intuitive to handle but a proper explanation of the very few parameters that are to be set is missing.

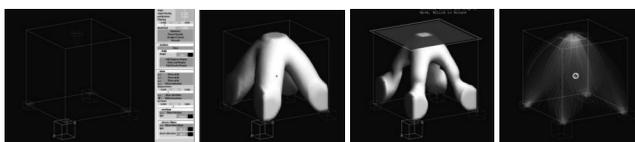


Figure 6. *Topostruct*: modelling, optimized structure, stresses, force distribution

The last analyzed free software is *TRINITAS* developed by Linköpings University, Sweden. [14] Its functionality is working as a classical FEM software with the extensions for running a TO. A simplification towards *Altair Optistruct* is not noticeable. It is therefore not considered in this paper.

3.2 Altair Optistruct

Altair Optistruct is a commercial FE-based TO program that was developed from the conventional FE dimensioning program *Altair Hypermesh*. It is using the same interface and is connected with the FEA solver *Radioss* which provides quantitative values of stresses and displacements before and after the TO. Compared to all free software it offers far more flexibility in modelling the geometry as well as defining load cases and importing or exporting data. Because of its considerably large functionality it is not intuitive to use and the possibility of mishandling is high.

4 CASE STUDY

The aim of this case study was the comparison of commercial and free TO-software to be able to evaluate the handling and the optimized solutions given by the free software. In cooperation with an industrial design agency the case of a foldaway shower seat was investigated. The shower seat is set up of a mount fixed to a wall, a seat and a pin that is connecting the two main parts. It is supposed to take up to 1500 N of weight of its user as the main load. Additionally a transverse force of 600 N may arise from each side in case of a side push. The upper surface of the seat was given by the designers as not to be changed. Underneath the seating the room is free design space.

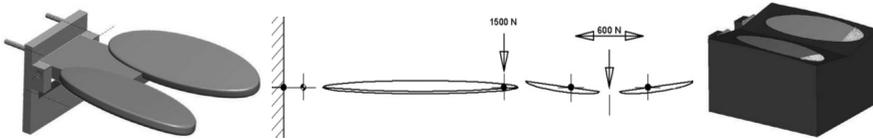


Figure 7. Initial shower seat to be optimized, applied loads, investigated load case

The case was chosen as it covers several interesting issues to be studied such as multiple load cases with forces of different weighting, dead load and the possibility of simplifying it by making use of symmetry. The simplification implies a slight error as both transverse forces are then acting at the same time, compensating each other. In the investigations, merely the seat and not the support is studied. To describe the reaction force from the mount onto the seat all degrees of freedom are taken of the upper surface of the crank of the hinge. The model was created in Pro Engineer and then imported into *Altair OptiStruct*. For the investigated load case in *Altair OptiStruct* see Figure 7 (right). For optimizing the seat with *Altair OptiStruct* most of the parameters are left in their default settings. The penalization factor is set to 2 and the “minimum member size control” filter is left turned off. The volume fraction is set to 0.3. In order to study the influence of the input parameters, four different cases are defined. In cases 1 and 2 the entire model is optimized, cases 3 and 4 make use of the symmetry so only half of the geometry needs to be built. In cases 2 and 4 dead load is applied. The gravity and transversal forces are weighted 1: 0.25. The chosen iso value is the smallest possible for a closed contour of the arm supporting the seating. The obtained results of *Altair OptiStruct* include quantitative dimensions, stresses and displacements (Figure 8).

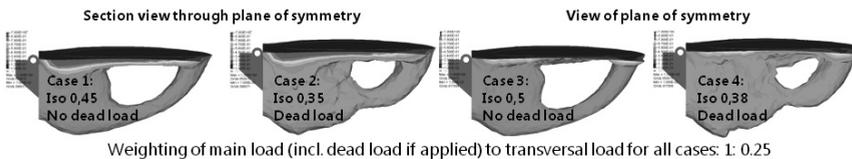


Figure 8. *Altair OptiStruct*: Optimized results for four different cases

To remodel the load-case of the shower-seat successfully, the free software needs to imply the minimum compliance design with a residual volume fraction, a 3D geometry, multiple load cases, weighting of forces and application of dead load to rebuild the more realistic cases 2 and 4. Additionally desirable for easy handling are a GUI and the possibility of exporting, importing and saving data. To obtain quantitative output data, input data such as dimensions, forces and material properties also need to be quantitative. None of the presented free software is able to weight the applied forces and to employ dead load successfully. Only 3D compliance design employs more than one load case. Still, to achieve comparability of the free programs with each other, *ToPy*, 3D compliance design and *Topostruct* are used to rebuild the shower seat using the simplified symmetric case 3 for all programs. With 3D compliance design case 1 is also designed. (See Figure 9)

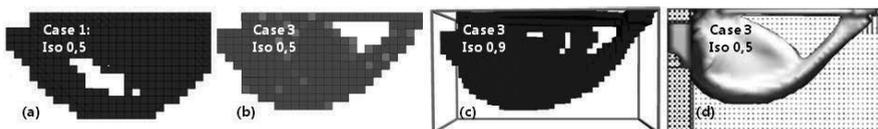


Figure 9. (a) 3D compliance design, (b) *ToPy*, (c) 3D compliance design, (d) *Topostruct*

If it is possible to define the same load cases, the optimized structures are very similar and differ mainly in their surfaces due to the coarser resolution of the free programs. Comparing the results proves that all analyzed software is based on SIMP. Thus they qualitatively deliver the same output.

5 CONCLUSION AND OUTLOOK

The analyzed programs mainly differ in the way of modelling geometry and load case as well as how the optimized output data can be further processed, depending on the exportable format. The most precise way of modelling the geometry is importing the data. Most realistic cases usually imply dead load, several load cases and forces of different weighting. Defining such precise cases and giving quantitative dimensioning is not yet applicable with free TO software. Although it is only possible to analyze simplified cases, the outcome of free TO is very similar to the results obtained with the commercial software *Altair Optistruct*. Thus all analyzed free programs are appropriate to offer sensible qualitative suggestions for optimized geometries to the user. Apart from *ToPy* this is achieved requiring less effort and being more intuitive than with *Altair Optistruct*. Some programs need some further development such as a GUI or the possibility of importing and exporting geometries. For all of the software a brief description of the input parameters would be useful. The second step ahead would be providing quantitative results and dimensioning.

Mainly intuitively operable, free TO software offer good quality results of optimized structures. This potential can be used in education and in industry. For industrial designers with no classical training in technical mechanics, TO will provide an effective support to create sound structures and finally more sustainable products. For engineers it offers a cheaper and quicker way to optimized components. Especially in education the use of free TO-software can have a motivating effect if reasonable results are achieved with less initial effort. Students can concentrate more on the technology and on the results of the TO than on the handling of software. The possibility of easily “playing” with load cases and automatically designing structures supports the understanding of basic mechanical concepts. As this paper points out, TO can be free of charge and does not necessarily require a profound knowledge of technical mechanics. It is a potential which is constantly expanding and improving.

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