

On Challenges and Solutions of Topology Optimization for Aerospace Structural Design

Wenjong Gu

United Technologies Research Center, East Hartford, CT 06108, USA, guwj@utrc.utc.com

1. Abstract

This paper identifies and discusses three challenges and their solution path and perspectives in the industrial practice of Topology Optimization (TO). It focuses on the SIMP method of TO for aerospace structural applications. The limitation to linear elastic condition by the SIMP method leads to the first challenge to adopt TO and address the structural functional requirements. The value proposition of TO is discussed. Three scenarios that trigger the use of TO are proposed. Drawn from the aerospace structural design setting, the traditional design process is compared to the TO driven design process. The integration of TO into the structural design process is emphasized for future development.

Commercial TO tools employ gradient based searching algorithm and obtain local optima for industrial size problems. The local optima may be non-unique and sensitive to the problem parameters. This leads to the second challenge to rationally validate the uniqueness of the topology optimized concept. This requires to develop a practical sensitivity study strategy to solve an individual TO problem with respect to the problem parameter changes. A cube example is illustrated to outline the generic questions for strategy development of the uniqueness and sensitivity study.

The third challenge is related to manufacturing feasibility and interpretation of the optimal topology. The topology optimized design is often not directly manufacturable. To convert optimal topology to a manufacturing design, moderate to significant manual modification of the topology concept is necessary. This user interpretation process of the TO results is subjective in nature and will add penalty to the weight/cost gain from the TO concept. TO must be integrated with the manufacturing process in order to be able to fabricate the highest performing topology at reasonable cost. It is important to develop practical rules and guidelines to interpret optimal topology.

The manufacturing challenge prompts further thoughts on the use of Additive Manufacturing (AM) in order to retain much, if not all, of the original organic yet complex optimal topology. This emerging area of combining TO and AM could be further explored for designing better Aerospace structures.

2. Keywords: Topology Optimization, Industry Application, Structural Design, Manufacturing

3. Introduction

Bendsoe and Kikuchi [1] proposed the homogenization method for Topology Optimization (TO) that was considered the start of the new era of TO. Bendsoe [2] further proposed the artificial density approach that was soon renamed to SIMP (Solid Isotropic Microstructure with Penalization) by Rozvany et al [3]. Since then, the SIMP method has received extensive research [4-6] and gradually became the de facto standard being adopted and implemented in nearly all commercial TO software. In recent years, TO has been increasingly acceptable in industries as the automatic tool for structural concept generation [7-12]. Rozvany [13] commented that such an increasing popularity of TO in a wide range of industries including automotive, aerospace, heavy industry, etc. is partly because of the successful development and promotion through commercial FEA software (such as OPTISTRUC, GENESIS, MSC/NASTRAN, ANSYS, TOSCA, AND ABAQUS). In the same paper, Rozvany pointed out that, for industrial applications, the dominating preferences for the TO tools are (1) low CPU time (2) generality of applicability, (3) reliability, (4) simplicity of implementation, and (5) simplicity of the topologies obtained. While these preferences are the recommendations for methods and software development, they also reflect the state of the art for the dominant commercial TO tools, in particular, OPTISTRUC [14] and GENESIS [15, 16]. In this paper, the author examines for the application challenges when one uses mature TO tools to execute the TO task for the real life structural component design. The focus is on the implementation aspect of the TO task based on the author's TO activities and prospective for aerospace structural design. The readers can seek other application publications [17-19] to familiar with the topics that is less covered in this paper.

The first challenge is associated with the limitation of TO addressing the structural functional requirements. While the SIMP method of TO is widely acceptable as an efficient technique for concepts generation in structural design, the method confines to linear elastic condition of structural system. In fact, the real life aerospace structural component design is very complex, involving but not limited to multiple loads, statics and dynamics, material and geometrical nonlinearities, multi-physics counting fatigue, thermal, and structural-fluid interaction. Section 4 will

examine the value proposition of TO in the design process and illustrates how to promote and integrate TO into the design process to meet functional requirements.

The second challenge is associated with the limitation of local optimum. Commercial TO tools such as OPTISTRUCT [14] and GENESIS [15, 16] employ gradient based searching algorithm in order to obtain optimum at minimal computational time for industrial size problems. However, the local optimum may be non-unique and sensitive to the design problem set-up and boundary condition changes. To rationally validate the uniqueness of the topology optimized design concept, it requires to execute a practical sensitivity study to solve the TO problem with respect to the problem parameter changes. Section 5 will address how to implement such sensitivity study strategy.

The third challenge is associated with the limitation of manufacturing feasibility and subjective user interpretation of the optimal topology. The topology optimized design, even being enforced with applicable conventional manufacturing constraints implemented in the commercial software, is often not directly manufacturable. To convert optimal topology to a manufacturing design, moderate to significant manual modification of the topology layout is necessary. This user interpretation process of the TO results is subjective in nature as the user may not fully trust the results, be unable to capture the key concept from the results, be unable to find a good manufacturing method. As a result, TO needs further integration with the manufacturing process in order to be able to fabricate the highest performing topology at reasonable cost. Section 6.1 will examine this challenge and recommend to establish practical rules and guidelines to interpret optimal topology.

The manufacturing challenge prompts further thoughts on the use of Additive Manufacturing (AM) in order to retain much, if not all, of the original organic yet complex optimal topology. This emerging area of combining TO and AM is very promising for designing better Aerospace structures and is discussed in section 6.2.

4. The challenge to addressing functional performance requirements

Optistruct manual [14] provides some explanations of the value proposition of TO: “in the concept phase of a design process, the freedom of the designer is limited only by the specifications of the design (Figure 1a). Today, the decision on how a new design should look is based largely upon a benchmark design or on previous designs. The decision making is based on the experience of those involved in the design process. Topology optimization can be introduced to enhance the process. The concept can be based on results of a computational optimization rather than on estimations”. [14] also provides Figure 1b for the design process using topology optimization. It states that “The overall cost of design development can be reduced substantially by avoiding concept changes introduced in the testing phase of the design. This is the major benefit of modifying the design process by introducing topology and topography optimization”.

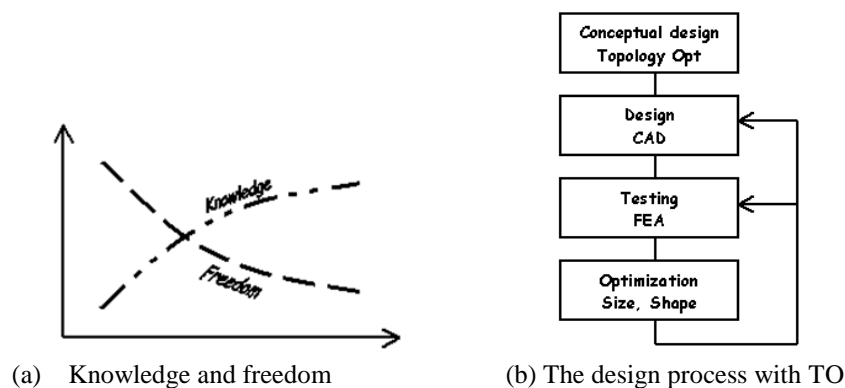


Figure 1: The value of Topology Optimization

The above statement successfully convinces the users that TO is an efficient automatic technique for concepts generation in structural design because, without TO, the only way to generate new structural layout concept is through brain storming by experienced engineers. The statement conveys that applying TO earlier in the design phase would have huge savings. However, such simple explanation is often challenged by the engineers and management who start to evaluate TO and look for the value proposition in greater details on how much the benefits are before their adoption of TO can take place. i.e., how much weight/cost/time will TO save? How much % savings from TO design concept will be eliminated in the final design? The second question naturally arises because the SIMP based TO cannot evaluate accurately complex functional performance (such as fatigue, acoustics, thermal etc) and will subsequently incur weight/cost penalty in the final design. While each structural

design problem is different so that the answers to two questions are difficult to be quantified, we can still provide reasonable value proposition analyses for three scenarios to address more qualitatively and less quantitatively on how much TO benefits:

Scenario A: Assess qualitatively the saving potential

Analyze if the structure design problem has been iteratively designed based on prior experiences. If no, this problem is suitable to be solved by TO as the current design may be over designed. If yes, assess whether the current design is already optimized through manual iterations over the years. The design that is less optimized and less understood will be the candidate for TO. In such situations, TO will provide good alternative solutions to the current design that may have big weight/cost savings. The TO results showing that the current design is nearly optimal in weight/cost is also great information for the designers and management. Regardless of the outcomes, TO success stories of similar structures from competitors could be very convincing for the pursuit of TO.

Scenario B: Limitation analysis

For the structural design problem, go down to the lowest limits of design thickness, span, number of ribs, material types and so on in order to get an idea on how low the weight/cost could go as compared to the current design. For example, for an aircraft wing structure, the skin thickness and rib dimensions can go down to the minima that are feasible, and compare the weight at this minimum condition with that of the current design. The difference provides an estimate on the maximum weight savings that can be reached. A nominal 20% or more would be attractive to the engineers and management to adopt the use of TO.

Scenario C: Accelerate concept generation under rapid changing requirements and time constraint

When the component design in the detail design phase requires modification due to rapid changes in component attachment locations and loads, such changes may be too big for the design engineer to develop an easy structural modification. In such situations, TO could work very effectively to shorten the design time by providing new configuration concept quickly.

The above three scenarios could be the triggers for the engineers and management to use TO. Nonetheless, the role of TO in the design process cannot be overstated for the reason mentioned before: its limitation to linear elastic condition. Figure 2a illustrates the real life simulation driven design process without automatic structural optimization. This is still a predominant practice as optimization only comes in as a plus point to add values. Figure 2a also views the importance of physical tests to validate the simulation. Figure 2b illustrates the process enhanced with TO for concept generation and shape/sizing for fine-tuning. The Box of TO intends to replace the box of concept proposal based on prior experience in Figure 2a. Each arrow represents a manual step done by the engineers. For the shape/sizing optimization, it is a standalone task if needed. The design process of many aerospace problems, such as design for fatigue, design for acoustics and design for crashworthiness, are currently still a manual iterative process because the establishment of a complete optimization problem is unrealistic or impossible. TO is employed at the beginning of the design process as triggered by scenarios A and B. TO solves the problem from the largest possible design space and may generate a near optimal concept to start designing with. This inherently avoids suboptimal concept that may be proposed based on prior experience in Figure 2a, and subsequently avoids long and tedious design iterations and possible excessive weight/cost upon completion. Scenario C is illustrated as the return to the box of TO from the box of Results Evaluation in Figure 2b.

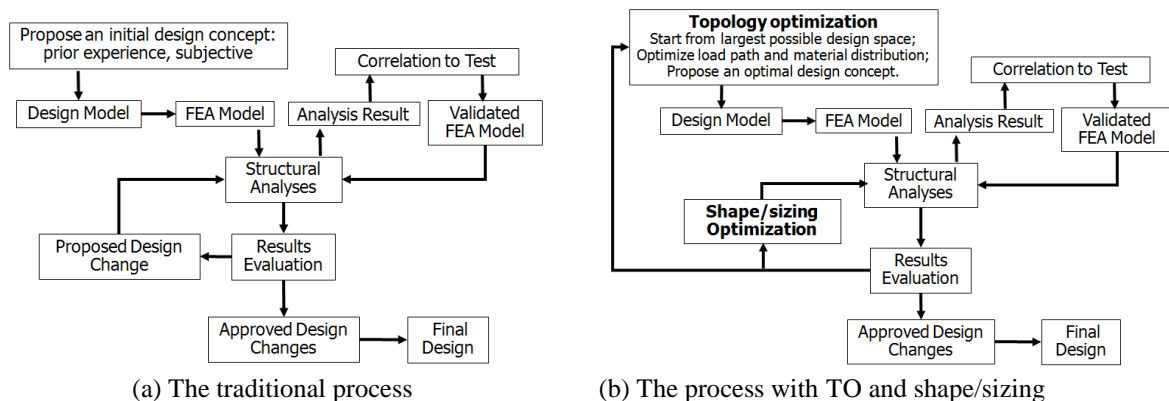


Figure 2: The structural design process comparison

This functional requirements challenge for TO has recently been addressed through an integrated and iterative fashion in optimization [18]. In the case of nonlinear crashworthiness responses, we can use the Equivalent Static Load (ESL) technique developed by G. J. Park and his associates [20]. This method is implemented in both OPTISTRUC and GENESIS. With ESL, GENESIS can be coupled with LS-DYNA [21] to iteratively solve the TO problem in GENESIS and the full crash analysis problem in LS-DYNA [22]. In conclusion, the integration of TO into the structural design process will be an area for continuous developments in the future.

5. The challenge to validate the uniqueness of the optimal topology concept

5.1. The optimization problem

The finite element based SIMP approach of the topology optimization can be formulated as follows:

$$\begin{aligned}
 &\text{Find } D = (d_1, d_2, \dots, d_N) \\
 &\text{Minimize } Compliance = U^T F \\
 &\text{Subject to } W(D) \leq W_i \\
 &\quad d_i^L \leq d_i \leq d_i^U, \quad i = 1, 2, \dots, N
 \end{aligned} \tag{1}$$

Where the design variable vector $D=(d_1, d_2, \dots, d_N)$ includes the density of each element in the structure, the total number of design variables is N ; the objective compliance is the product of displacement vector U and force vector F ; $W(D)$ and W_i represent the structural weight and its upper bound, respectively; d_i , d_i^L and d_i^U are the i -th density design variable, its lower and upper bound, respectively. Under the SIMP framework, the valuable d_i is continuous and varies between its lower bound and upper bound; Theoretically, its lower bound d_i^L is 0, representing the state of void. Its upper bound d_i^U is the full density of the assigned material, representing the state of solid. Intermediate values of density represent fictitious material. The stiffness of the material is assumed to be linearly dependent on the density.

Popular TO software such as OPTISTRUCUT [14] and GENESIS [15] solve the above problem by the gradient search algorithm with the use of advanced approximate concepts. The computational cost for solving a TO problem is comparably the same magnitude as that of shape or sizing problems for similar size of the model. This makes TO very appealing to industrial users as the results can be efficiently generated.

5.2. The cube problem

Using Hypermesh and Optistruct [14], a TO design problem is modeled as shown in Figure 3. The complete model design space in Figure 3a is fixed in the four corners and loaded at the center. Due to symmetries, this model is simplified as a cube design space as shown in Figure 3b. This cube model accounts symmetric boundary conditions and fixed in one corner. The load is reduced to one fourth of the original. The total number of the solid elements of the cube is 125000.

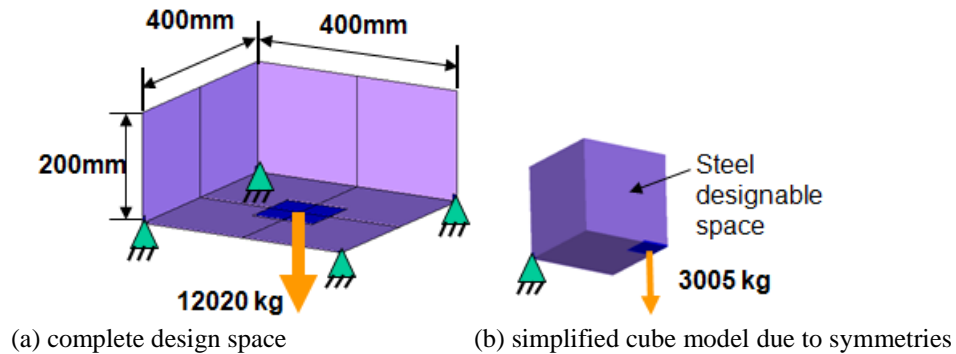


Figure 3: The cube example

The weight target is 20 kg as compared to the weight of full cube 60kg. This problem is solved in OPTISTRUC and converged at iteration 16. The density of the initial design is uniformly assigned to 0.9. It takes 76 minutes to run in a Linux workstation with Intel Xeon CPU X5550 at the CPU speed 2650 MHz. The optimal topology at density cutoff of 0.5 is shown in Figure 4. It is obvious that the optimization converged to a local minimum with the majority of element density at or near full density 1.0.

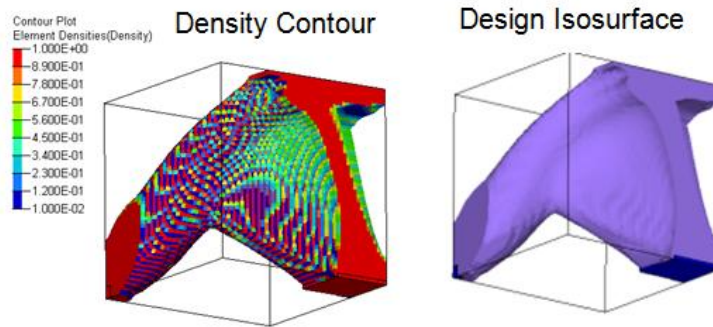


Figure 4: Density contour and isosurface of optimum

While it involves minimal efforts to obtain such an optimal configuration concept, the adoption of this concept is not readily warranted. There are at least six practical questions to be answered:

1. What is the effect of the initial density changes to the optimum?
2. What is the effect of the fixed location changes to the optimum?
3. What is the effect of the design space extension to the optimum?
4. What is the effect of the load magnitude changes to the optimum?
5. What is the effect of the mesh resolution to the optimum?
6. What is the effect of the weight target changes to the optimum?

In industry practice, the above questions will activate the follow up validation study on the uniqueness and sensitivity of the TO concept solution. A systematic exploration strategy is usually developed including selecting variables and conditions as implied by the above questions. For example, question 6 will lead to solve and generate a Pareto frontier curve of weight target v.s. optimal compliance. The curve will provide a good indicator on what range of the weight target is the most effective to stiffness gains. Another task could be drawn from both question 2 and 3 to formulate a simultaneous topology and shape optimization. The shape optimization part is to change the fixed locations and boundary surfaces of the design space. Of course, any reasonable design of experiment study can be pursued from the above questions.

Many publication of TO industrial application demonstrate the effectiveness of one TO concept but often lack of a systematic sensitivity study as suggested from the cube example. Such study could render additional opportunities to find better or alternative configuration concepts. Gu et al [12] demonstrates in detail the need and effectiveness of such a sensitivity study on the topology optimization for a wind turbine hub structure. The author envisions such studies will become a standard task to address the challenge of validating the TO concept.

6. The challenge to address the manufacturability of the optimal topology

6.1. User interpretation for conventional manufacturing

Optimal topology can often be not directly manufacturable. The optimal topology concepts, in general, can be transformed into a manufacturable CAD design through a manual interpretation process by the design engineers and structural engineers. The limitation of manufacturing feasibility of computed optimal topology is a major challenge for the adoption of TO in the design process as moderate to significant manual modification of the topology concept will potentially eliminate the savings obtained from the TO concept. One can argue that TO is mainly for simplified FEA models in order to generate concepts without paying much attention to detail design constraints that are difficult to model and may only add minor penalty to the weight and cost. This fact, however, complicates the potential benefits assessment as the gain from TO and the penalty from concept interpretation into the CAD design cannot be evaluated until the design is validated. Furthermore, the user interpretation process itself is subjective in nature as the user may not fully trust results, be unable to capture the key concept from the results, be unable to find a good manufacturing method. As a result, TO needs further integration with the manufacturing process in order to be able to fabricate the highest performing topology at reasonable cost.

Recent years have witnessed an increased variety of applicable conventional manufacturing constraints implemented in the commercial software [14, 15], such as Member Size Control, Draw Directions, Extrusion Constraints, Pattern Repetition, Pattern Grouping implemented in OPTISTRUC [14, 19]. However, these manufacturing constraints are still limited. They are also constrained by the simplified TO model that usually does not have finer meshes to count on small manufacturing features. To address this challenge, the commercial TO tools will keep improving and adding its manufacturing constraint capability. The practical rules and guidelines to interpret optimal topology could also be established for each conventional manufacturing method in order to guide

the engineers to interpret better.

6.2. Use additive manufacturing for optimal topology

Figure 5 shows the CAD model of the optimal topology concept of the cube example in section 5. The CAD is generated based on the STL output of the optimal topology isosurface. From Figure 5a, it is observed that the optimal configuration has an internal void that is incompatible with conventional manufacturing methods. From figure 5b, it is observed that the full configuration that has complex curved surfaces can be modified manually for casting or forging fabrication if the void is filled. However, enforcing casting or forging constraints, whether through manual interpretation or manufacturing constraints in the TO software, will generate the design concept of the same stiffness but higher weight because the constraints narrow the design space and penalize the weight. This fact prompts the thought to use Additive Manufacturing (AM), also referred to as 3D Printing, to fabricate this concept. It will retain the original void coming from optimum and represents the maximal stiffness structure.

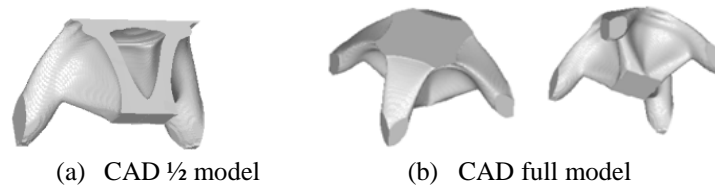


Figure 5: CAD model of the optimal concept

The idea of using additive manufacturing for optimal topology is relatively new. Some early works use AM to fabricate smart materials designed by topology optimization [23-25]. With recent advancement of AM [26], research and application of topology optimization for AM becomes very active. Kapania and his coworkers [27-28] have been developing topology shape, and sizing optimization framework and software for Unitized Structures using Electron Beam AM process. They envision an environment in which design and manufacturing, using modern information technology, would be integrated into one step, consistent with the modern trend of employing unitized structures. Tomlin and Meyer [29] optimized an Airbus A320 nacelle hinge bracket for Additive Layer Manufacturing. Lynch et al [30] designed the cold sprayed structural mount by topology and shape optimization for weight minimization under stress constraints. The shape variables of that study are defined by HYPERMORPH [14] under cold spray AM constraints. Brackett et al [31] gave an overview of the issues and opportunities for the application of topology optimization methods for additive manufacturing. This emerging area of combining TO and AM is very promising for designing better Aerospace structures in the future.

7. Conclusion

In the industrial practice of Topology Optimization using the SIMP method and commercial software, three challenges, related to addressing the structural functional requirements, optimal concept uniqueness and manufacturing feasibility, are discussed with their solution path and perspectives.

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