

Integrated Shape and Topology Optimization - Applications in Automotive Design and Manufacturing

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ABSTRACT

This paper presents applications for an integrated shape- and topology (IST) optimization approach of structural systems. IST introduces additional geometric and loading conditions to the design space of topology optimization. That is, the design space for a Solid Isotropic Material topology optimization algorithm as well as the complex surrounding structure can be varied. Importantly, large scale shape variation is performed *in conjunction* with topology optimization, rather than post the topology optimization step. This paper discusses the relevant optimization and parameter studies for automotive design. The case studies presented range from single parts to highly complex assemblies. Automobile body structures that combine extruded beams with cast joints are an important application of IST.

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LIGHT-WEIGHTING IN THE AUTOMOTIVE INDUSTRY

In structural mechanics, the requirements for structural elements and systems are highly complex. This is especially true for the very competitive automotive industry, where engineers are expected to shorten development and test time, while also cutting material and production costs. Moreover, in the quest for reducing fuel consumption and CO₂ emissions, light-weighting of structures is essential for more energy efficient transportation systems.

When assessing body structures of today's automobiles, the market is predominantly made up of thin walled pressed and welded steel structures. This solution has several advantages. Steel is an inexpensive and very versatile material, the forming processes and joining technologies (mostly spot welding) are well understood, and the employment of high strength steels has facilitated a significant improvement in crash safety performance while limiting the mass penalty.

Regardless of the strength of this approach, the use of materials such as aluminum, magnesium and fiber reinforced composites promises even further reduction in weight while also offering new design possibilities. Examples include highly complex shapes of castings, or fiber reinforced composite materials that are tailored to meet specific

loading conditions. Furthermore, the emergence of large scale metal additive manufacturing in the aerospace sector may see this process transfer to the automotive sector, with an associated increase in the geometric complexity of future automotive bulk part designs.

Nevertheless, before such materials can be used in large volume production, there are a variety of issues to overcome, such as higher material cost, longer production cycle time (e.g. compared to sheet metal stamping), and the development of appropriate joining technologies.

BACKGROUND: SIMULATION AND OPTIMIZATION METHODS

In structural design, simulation and corresponding optimization methods have become indispensable. An important tool for the design of load bearing parts has become the topology optimization method [1,2]. Homogenization based approaches have been widely adopted. Here, the engineer starts with a feasible design space and applies loads and constraints. The topology optimization algorithm returns a structural layout describing main load paths in the form of a density distribution on the design domain [3,4,5,6].

In more detail, the designer starts with an initially solid volume describing the permissible design region - the “package space” - divided into a discrete mesh of finite elements. After applying loads and constraints the optimization algorithm then determines in an iterative process whether a region in the design space should contain material or not. In practice, most algorithms also assign intermediate densities, such as ‘a design region is present to a level of 50%’. This results in a density distribution $\rho: \Omega \rightarrow [0,1]$ on the package space Ω . Thus, the topology optimization algorithm can be viewed as a material distribution method.

There are two main approaches to define the objective function for the topology optimization. The first aims to find a density distribution $\rho: \Omega \rightarrow [0,1]$ on the design space Ω that minimizes a certain functional such as the global compliance: Find ρ such that $f = \frac{1}{2} u^T K u$ is minimal, while the amount of used material equals a fixed percentage portion of the original material (‘mass fraction approach’).

Another approach is to find a density distribution with minimum overall mass, such that a set of constraint (e.g the displacement at some specific points) is minimized: Find

$$\min_{\delta} \int_{\Omega} \delta \, d\Omega \quad \text{subject to} \quad g_k(\delta) \leq 0.$$

Once the algorithm has derived a suitable density ρ , the next step is to either fine-tune the resulting shape or else translate it into multiple manufacturable parts. Topology methods are predominantly useful for single parts, for example, cast aluminum suspension components. For complex assemblies, the topology results require considerable interpretation and rework by the designer. In this context, shape optimization methods are applied only *after* the topology optimization to reduce local stresses and to incorporate detailed manufacturability requirements [7,8].

Although topology optimization methods can generate load path proposals for the design of complex assemblies such as automobile body structures, they cannot produce the detail required to properly describe cross-section, or the intricate structure of a multi-layered panel with specific fiber orientations. Moreover, dynamic crash load cases have to be approximated by linear static equivalent loads. So, for a detailed CAE simulation, a more realistic finite element (FE) model representing the real geometry is needed. To achieve this level of detail, typically a CAD geometry is created, which is then translated into a FE simulation model, and CAE analysis with respect to stiffness, strength, crash performance and other aspects can be carried out. A specialized approach in this concept finding stage is offered by the parametric geometry tool SFE CONCEPT, which is designed to create finite element models of complex thin walled sheet metal structures. It is especially useful in the early design stage, where detailed geometry may not yet be available, or where the designer still has the freedom to modify the structural layout [9,10]. SFE CONCEPT provides an implicit parametric geometry description, where intuitive shape design variables can be defined and result in consistent complex geometry [11,12]. After a geometry update in batch-mode, the integrated shell mesher generates a consistent finite element model, which is particularly well suited for 2D elements. Today, SFE CONCEPT is mainly used in the

automobile industry for early concept development of body structures. Crash related load cases are of particular importance [13,14]. One of the advantages of SFE CONCEPT is the ability to quickly assess large scale parametric shape modifications of a complete body structure including connections such as spot welds and adhesives [15,16]. Despite its many strengths, SFE CONCEPT's ability to generate load path information is limited to exchanging predefined structural members [9].

In this paper, we present a number of classes of structural optimization problems. The use of the Integrated Shape and Topology method to combine parametric geometry and topology methods is explored. Of particular interest is the application for complex automobile body structure, where the combination of parametric shape variation and the topology optimization for cast joints is examined.

COMBINATION OF PARAMETRIC SHAPE VARIATION WITH TOPOLOGY METHODS

The IST approach enables the integration of Solid Isotropic Material with Penalty (SIMP) topology methods with large scale parametric shape modification. Here we do not consider shape design performed as an additional step after topology optimization, which is a field of research in its own right [17,18]. Rather, we show that parametric shape modification *before* a topology algorithm adds a new dimension to the topology method. While a traditional topology optimization process starts with a fixed input design space, IST includes a parametrically variable structure as well as an adaptable design space for the SIMP algorithm (see Figure 1).

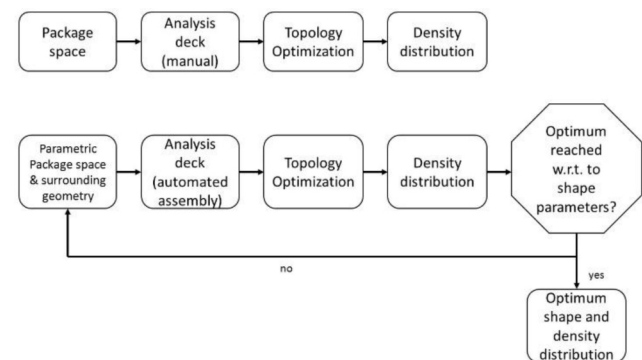
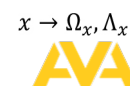


Figure 1. Schematic comparison between traditional topology optimization process (top) and topology optimization with integrated large scale shape variation (bottom).

An introduction of the implementation of the IST process is given in [19]. We provide a short summary here. Applying IST, the engineer generally starts with the manual creation of a parametric geometry model, including a set of shape design variables $x = (x_1, \dots, x_n) \in R^n$. The geometry consists of a part Ω_x that will be subjected to topology optimization, while Λ_x is not. Importantly, the geometry $\Omega_x \cup \Lambda_x$ is not fixed. Rather, for each set of design variables x , a different geometry model

will be created.



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Next either a Design of Experiments (DOE) or an optimization loop is conducted. The examples use Altair Hyperstudy and Dakota [20] to perform the optimization study. A single iteration in this loop consists of a geometry model update, the assembly of the analysis model, running of a SIMP algorithm, and finally the extraction of analysis results. Additional plug-in functions can be defined and integrated. IST provides a flexible scripting language to describe the process flow. An important step is the automated assembly of the finite element analysis model that needs to happen for every iteration. To facilitate this process, IST reads finite element data, creates connections between parts, applies loads and boundary conditions, defines specific grids for measurement of displacements, as well as offering many more useful features. This results in a finite element analysis model $\Omega_x \cup \Lambda_x \cup \Gamma_x$ where Γ_x stands for the connections and boundary conditions. The next step is to initiate a SIMP topology optimization, for which Altair Optistruct is used [21]. Considering constraints $g_j(x)$, a density distribution δ_x on Ω_x is determined together with some performance measure, which in many cases will be the overall mass M :

$$M(x, \delta) = \int_{\Omega_x} \delta \, d\Omega_x + \int_{\Lambda_x} 1 \, d\Lambda_x$$

Depending on the objective function values determined by the finite element solvers, an outer optimization loop designates new values for the shape design variables x . This closes the geometry update loop.

The presented method allows two major new approaches: First, the initial design space that goes into the topology optimization algorithm can be subject to large scale parametric shape variation. Second, the topology design volume may be part of a complex system, which itself is subject to parametric optimization. This approach adds a geometric dimension to the design space for topology optimization and to the system it is embedded in, and largely increases the size of the optimization space open for exploration not possible in existing tools, since they do not offer a parametric description of geometry and package space.

APPLICATION OF IST, SELECTED EXAMPLES

In the following sections, three examples are presented, where the application of IST combines parametric shape modification with subsequent topology optimization.

The specific examples have been selected to demonstrate the relevance of this approach to the automotive industry. They highlight the versatility of IST in applications ranging from single load bearing parts or multi-piece assemblies to highly complex systems such as entire automobile body structures. For solid components (as opposed to thin walled stamped parts), manufacturing considerations are included to ensure that components can be either die cast or extruded.

In the first example, we look at a cast aluminum bracket mounted to an engine block, used to attach an air conditioner pump. IST tools are applied to simultaneously find load path layouts and optimal locations for the attachment bolts. With 11 geometry design parameters, genetic optimization proves to be effective, and the potential mass

saving by combining the optimization for attachment point positions and topology is shown to be high. In a more general sense, IST allows us to combine standard topology optimization methods with the optimization of boundary conditions.

In the second example, a two-piece clamp, made from extruded aluminum, is optimized. The geometry of the components is optimized, and topology methods are used to minimize mass. In this type of application, where manufacturing requires extruded parts, IST is able to satisfy the extrusion constraint and optimize the shape of the components.

The third example showcases the parametric shape variation for an automobile body structure, combined with the topology optimization of cast connection joints. This class of application integrates complex parametric shape variation with the topology design of cast joints, and may become particularly useful for new approaches in the design and manufacturing methods of automobile body structures, where relatively simple extruded beam members are combined with complex shapes of cast joints. Here IST integrates complex thin walled sheet metal structure, extruded beam members and complex cast joints. It can determine a trade-off between necessary cross-section dimensions and size/topology of cast structures.

Application 1: Integrated topology optimization of a solid bracket while optimizing the positioning of attachment bolts

Problem Setup

In this example, we demonstrate the application of IST when determining a topology optimized solid bracket design in conjunction with the optimization of the positions of attachment bolts. Figure 2 shows the design space for a bracket (in light blue), attached to an engine block (dark blue) with four bolts (red). An air conditioner pump (yellow) is bolted to the bracket with three bolts (green).

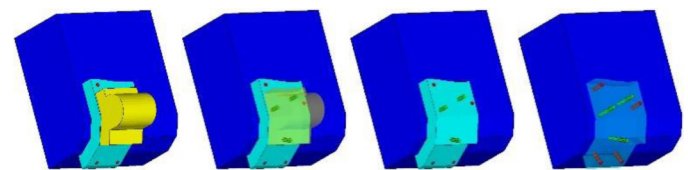


Figure 2. Engine block (dark blue) with attachment bracket (light blue) holding an air conditioner compressor unit (yellow). The position of the bolts are subject to parametric modification. The attachment bracket is subject to topology optimization.

It is standard practice to employ topology optimization to determine a concept load path design for the bracket. The design target in this case is to minimize the mass. As a critical constraint we require that the first Eigenfrequency of the system is not lower than 950 Hertz, so as to avoid possible resonant frequencies at low engine revolutions. A draw constraint is applied, to make sure that the part can be manufactured in a die cast process using a two piece die.

The exact positions of the bolts can make a significant difference to the static and dynamic performance of the design. In this case, the engineer has the design freedom to modify the attachment location of