Automated Derivation of CAD Designs from Topology Optimization Results

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Abstract

Topology optimizations are gaining track in many development processes, especially in designing large structural components such as railway car bodies. This paper proposes an automatic process to derive design proposals from SIMP topology optimization results in early product development stages. The topologies are interpreted as truss-like structures in order to be modelled using beam elements in FE or CAD applications. In a first step, a wireframe is extracted by using a voxelization approach with subsequent skeletonization and junction identification using flood-fill algorithms. The wireframe can already be used as a basis for a parametric CAD design since it follows the topology optimization result closely. In order to extrude beam sections along the wireframe axes, cross sections are extracted from the topology optimization result. This is done by first matching the geometric outline of a topology branch to basic shapes such as rectangles. These shapes are refined by identifying the load case of each branch which is achieved by evaluating the stress distributions in a branch of the topology optimization. The consolidated result is a model consisting of beam elements which can further be processed in an FE or CAD application. The process enables a faster design exploration in the early product development process with the goal of achieving lightweight designs.

Keywords: automation; topology optimization; virtual product development process

1. Introduction

Designing lightweight vehicles requires the use of modern design tools and algorithms in order to realize the highest possible lightweight design potential. Among these tools are topology optimizations. They are becoming more and more commonly used in various product development processes, including the railway industry, ranging from the conceptual design of whole car body structures to single structural components such as levers or brackets. However, properly interpreting topology optimization results and turning them into feasible designs poses an engineering challenge that requires both specific know how and manual design work.

The presented research proposes a comprehensive process chain that can considerably reduce the effort and time to successfully interpret topology optimization results. The automatic software tool generates CAD design proposals which can serve as a starting point for a design engineer’s creative work. The tool can be used by researchers and engineers from various industries to increase development speed in the early product development stage, allowing the faster exploration of more designs and, thus, leading to a better overall lightweight design. The developed process is part of the project Next Generation Train (NGT) in which the German Aerospace Center (DLR) has been developing high-speed and regional passenger trains as well as the high-speed freight train NGT CARGO [1].

2. Development process of large structural components

2.1 Topology Optimizations

Topology optimizations are based on the finite element method (FEM) where a part is represented by a mesh of elements. An element, in turn, consists of connected nodes, whereas the number depends on the type of element. Two-dimensional elements can, for example, be quadrilaterals whereas examples for three-dimensional elements are hexahedrons. Elements are connected with each other at their nodes, forming a mesh. Forces and boundary conditions can be applied on this mesh. The results of an FEM analysis typically are nodal displacements and elemental stresses. Topology optimizations use this information to calculate the ideal material distribution within a given design space. This way, load paths within a structure can be identified.

The developed process is based on topology optimizations using the solid isotropic material with penalization method (SIMP) which yields density distributions for elements within the design space [2]. In short, an element density-based topology optimization varies the relative element density for each element depending on the stresses and displacements each element is subject to and depending on the optimization objective (such as “minimize the mass of the structure”) and constraints (such as “only allow a certain deformation at this point”). The relative element density is the scalar value of the current density divided by the original (full) density of the material, meaning its value varies between 0 and 1. A value of 1 means that this element is vital for the load distribution within the design space. Contrarily, an element with a density close to 0 does not contribute to the stiffness of the structure. The elements with a high element density carry most of the load and, thus, depict load paths within the design space. By using a density threshold, elements with a lower relative element density than the chosen threshold will be masked from view, making the load paths visible. In case of the developed process, elements below the threshold will be ignored from any evaluation.

Figure 1 (top) shows a complex topology optimization result of the high-speed double-deck rail vehicle “Aeroliner”, developed by DLR for operation in the United Kingdom as part of the Rail Safety and Standards Board’s (RSSB) innovation programme “Tomorrow’s Train Design Today” [3], [4].

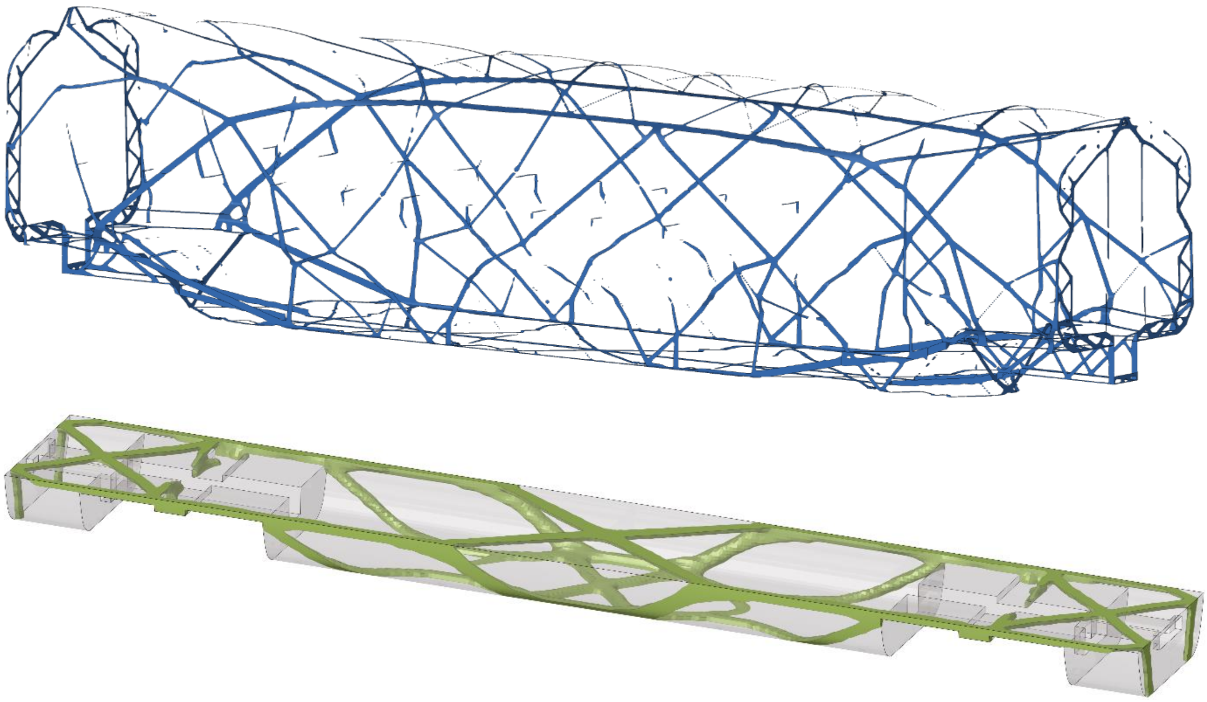

Figure 1: Topology optimization of the Aeroliner car body (top) and NGT CARGO undercarriage (bottom)

Figure 1 (bottom) provides a simplified topology optimization result of the undercarriage of the NGT CARGO, also developed by DLR for transporting low-density high-value goods [5]. This optimization result will serve as an example for the application of the developed process throughout this paper.

2.2 Interpreting topology optimization results

Topology optimization results by themselves are unsuited for direct application in a manufacturable product design (except for 3D-printing). The information needs to be interpreted and converted into structures which can be built with regard to material properties as well as budgets. This process requires time and skill. A starting point can be the creation of a wireframe skeleton which represents the optimal load paths in a CAD program. The wireframe can then serve as a parametric base to which subsequent operations like extrusions are referenced. The process of deriving a wireframe is also the first step in the developed automated process.

The element density distribution of a topology optimization often creates a truss-like structure. As such, deriving models based on individual beams forming a truss structure is a viable path to choose. Doing this by hand is a time-consuming task since each beam needs to be analysed for its size and the possible stress distribution it is under. Most beams within a truss structure are usually subject to tension-compression load, though, bending and torsion loads are possible as well in a topology optimization since they do not form a perfect closed truss structure. Free-hanging beams are possible and especially these may be under bending or torsional load. The stress data created by an FE calculation is made up of stress tensors for each element containing normal stresses $(\sigma_x, \sigma_y, \sigma_z)$, shear stresses (τ_{zx}, τ_{zy}) and von Mises stresses. Principal stresses and main stress axes can be calculated from these results, which is featured in the automated process.

3. Automated process for generating CAD design proposals

The fully automatic process chain consists of two main steps: extraction of a wireframe model and derivation of cross sections. The process is depicted in Figure 2. The main steps themselves consist of various sub-steps.

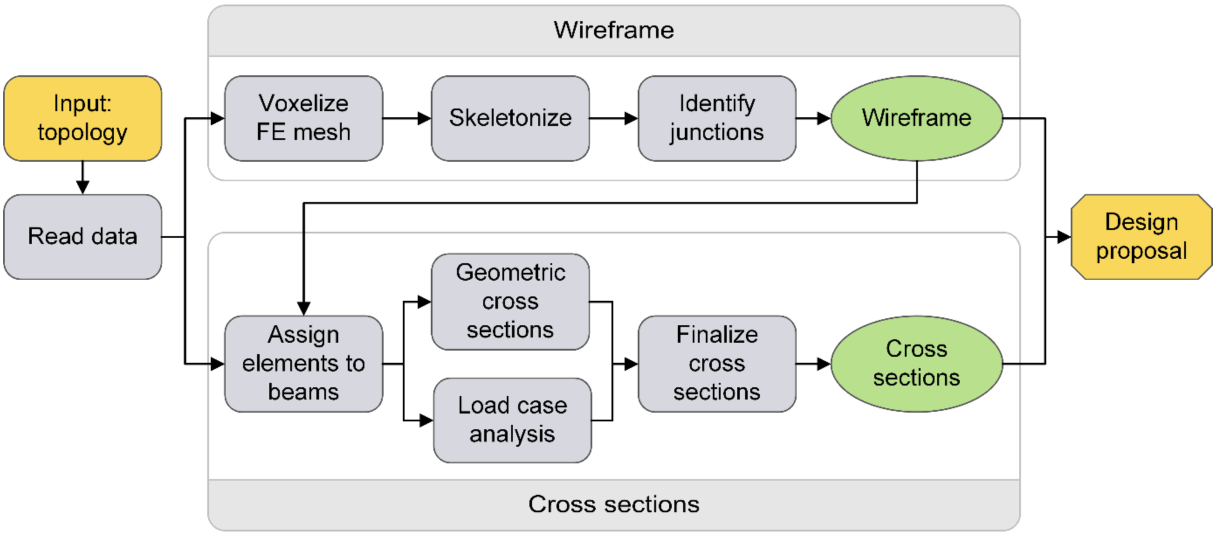

Figure 2: Automated process for deriving design proposals from topology optimizations

While there is a broad range of research in specific fields like image processing in itself, there are few research teams chaining algorithms from different disciplines together and, thus, actually tackling the gap between topology optimization results and CAD designs (see for example [6] and [7]). This research aims at closing this gap with a scientific approach.

3.1 Wireframe extraction

At first, the topological finite element (FE) mesh-based model is filtered using the relative element density results from the topology optimization, deleting all elements with a relative density below a configurable threshold. Figure 1 (bottom) shows the filtered optimization result of a railway car undercarriage. The three-dimensional design space of the model is then discretized with a regularly spaced grid – voxels. The filtered FE mesh is converted into a voxel-based representation. This representation of the topological model is then thinned using a well-established skeletonization algorithm. From the still voxel-based but one-voxel-thick skeleton lines, structural voxel areas (junctions) are detected where three or more skeleton lines join together using flood-fill algorithms. The centres of these voxel structures are then addressed and connected with lines, creating the wireframe model. Figure 3 shows the wireframe model of the railway car body from Figure 1 (bottom).

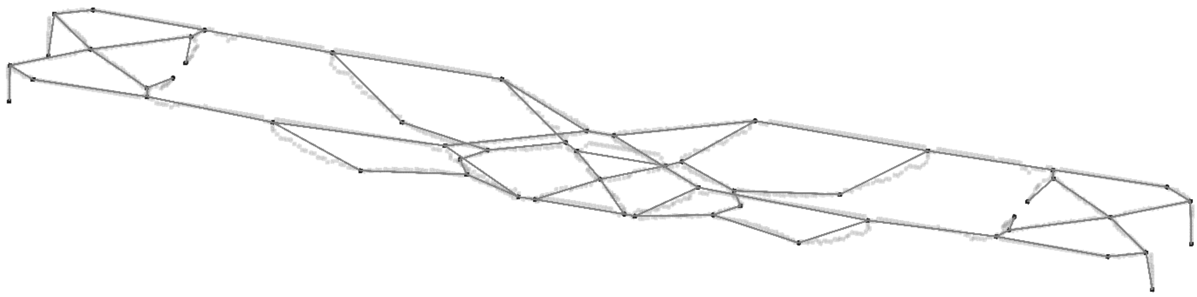

Figure 3: Wireframe skeleton of the NGT CARGO undercarriage

The voxelization approach for extracting the wireframe model represents a unique strategy in the application of generating derivative models from FE meshes. It allows the use of efficient image processing algorithms in the subsequent process steps of extracting a wireframe. Furthermore, it decouples the wireframe process from the syntax of the FE solver, making it easier to support different FE solver syntaxes since the actual wireframe process does not need to be adapted. Lastly, the decoupling from the FE mesh makes the wireframe process steps semi-independent from the arbitrary representation of the FE mesh quality since finite elements in a mesh can vary greatly in size, form and connectivity.

3.2 Cross section extraction

Using the wireframe model, it is possible to segment the topology model into individual beams. Each finite element of the topology optimization is assigned to the nearest beam (by Euclidian distance from an elements center of mass to the beam axes). According to Figure 2, the cross section extraction consists of two steps: geometric cross sections and load case analysis; each performed individually for each beam in the model.

In the geometric cross section extraction (Figure 4), the finite elements are condensed into points at their center of mass. A beam therefore consists of a point cloud and a central beam axis. Each beam is then cut multiple times perpendicular to its axis, generating several beam segments (Figure 4, left). These are compressed along the beam axis leaving two-dimensional point clouds (Figure 4, second from left) which are analysed for their geometric outline using shape detection algorithms. Several are supported, such as the χ-shape algorithm [8]. The found outline is compared to a library of geometric shapes, such as rectangles or circles. The closest match is chosen for each beam segment (Figure 4, third from left). Lastly, the individual beam segments are superimposed, averaged and a final shape is identified (Figure 4, right), concluding the geometric cross section analysis by providing a geometric shape with certain dimensions for each beam. This step is highly dependent on the chosen element density threshold, as is a manual interpretation of a topology optimization result.

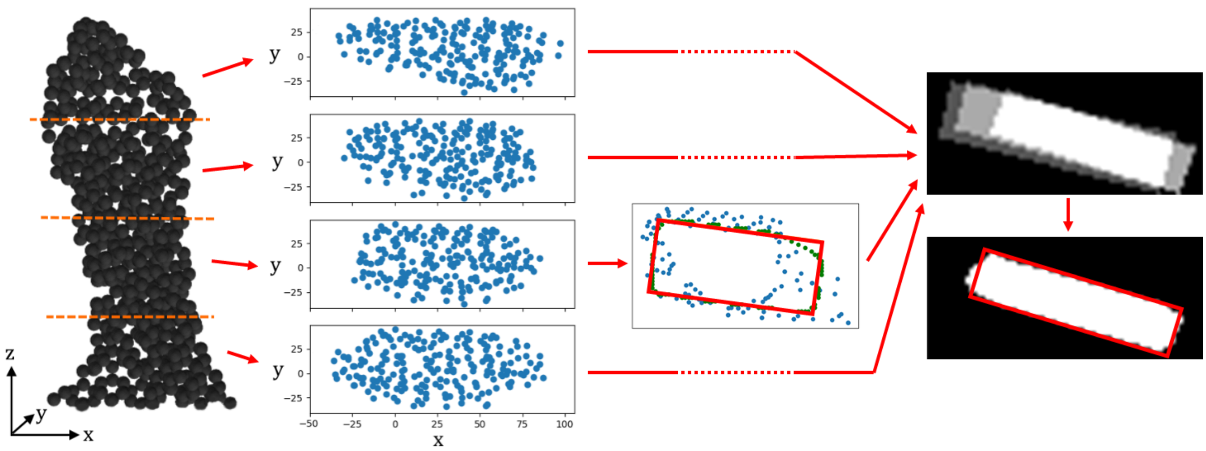

Figure 4: Geometric cross section analysis for beam consisting of a point cloud

The second step of the cross section extraction, the load case analysis, is also performed for each beam and its assigned finite elements, now using the stress tensor results from the topology optimization. The goal is to identify a basic load condition of each beam (tension/compression, bending, torsion). For this, all finite elements of a beam are condensed along its longitudinal axes (from the wireframe), as displayed Figure 5 (left) for a beam under bending load. Several stress distributions are graphed along a rotating vector v. Linear graphs are fitted for the individual distributions. The graph with the least error is then analysed for typical properties of supported load cases. For example, a pure bending load case features a linear stress graph and symmetric positive/negative maxima, as displayed in Figure 5 (right). Each supported load case receives a confidence score whereas the highest confidence score indicates the load condition of a particular beam.

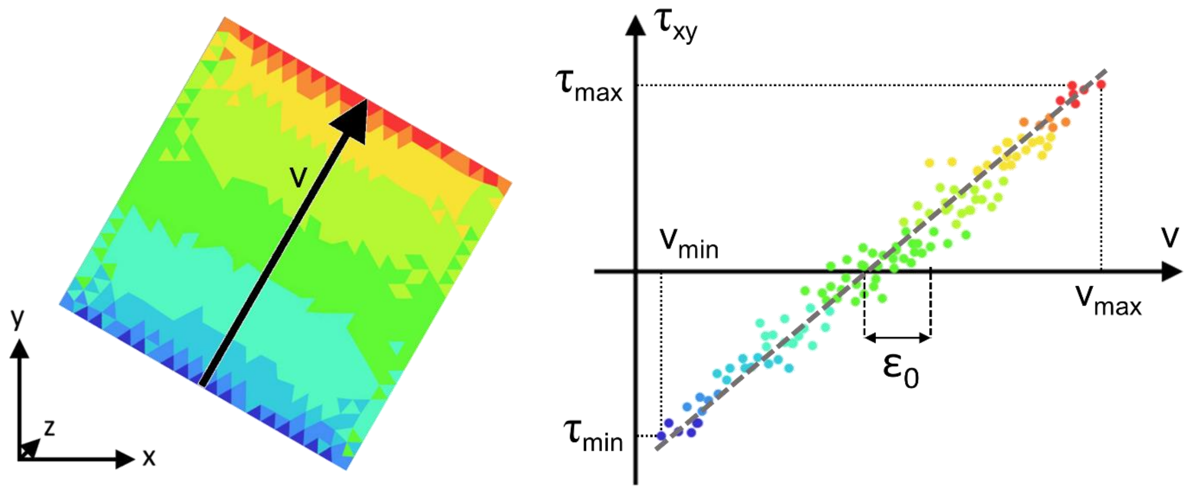

Figure 5: Load case analysis for a beam under bending load

The final step in the cross section extraction is finalizing the gathered information. The geometric shape and the identified load case for each beam are compared and a suitable cross section is chosen from a library of cross sections such as I-beams or round standard profiles. For example, a beam under bending load will receive an I-beam-profile with a suitable cross section area, modulus of resistance and mass compared to the topology optimization. Figure 6 shows the extracted cross sections for the NGT CARGO undercarriage.

3.3 FE validation

Combining the wireframe model with the derived cross sections, a first design proposal is achieved (Figure 6). In order to assess the validity of the quality of this design, a new FE model is generated combining the wireframe and the cross sections with the loads and constraints from the original topology optimization model.

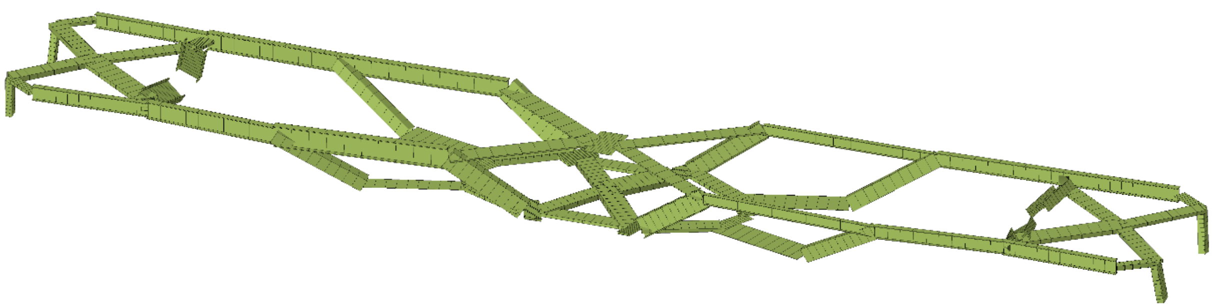

Figure 6: Automatically derived model using beam profiles in an FE application

This new validation model is used to perform a static FE analysis. The results provide information whether the proposed cross sections are suitable or need adjusting. Highly stressed cross sections can be adapted and the process repeated until the model performs well. As a final result, a design proposal can be exported as a CAD model.

4. Conclusion

This paper introduces an automatic process which supports design engineers in the development of lightweight vehicle designs. The process derives design proposals from SIMP topology optimization results. The topologies are interpreted as truss-like structures and modelled as beam elements in an FE application. After manually selecting the desired element density threshold, the developed process automatically extracts a wireframe by first converting the model into a voxel image representation. The voxel image model is then skeletonized to only possess one-voxel thick branches. Next, junctions are identified where more than two branches meet. By connecting the junctions and possibly smoothing the newly created lines to match the initial voxel model, a wireframe skeleton is created which can be used as a basis for a parametric CAD product design. Then, cross sections are derived in order to be able to extrude beams along the branches of the wireframe. For this, the geometric outline of each branch in the topology optimization result is detected. The outline is fitted to a library of geometric shapes, providing a basic shape information for each beam. To refine the beam shape, the elemental stress results from the topology optimization are evaluated by condensing the element's stress tensors of a branch into a 2D image from which a stress distribution are plotted. The distributions are fitted with linear graphs to detect typical load conditions such as tension/compression, bending and torsion for each branch. The geometric as well as the stress information is consolidated, leading to a cross section proposal for each beam. With the wireframe and the cross section information, the model is recreated in an FE application where it can be further processed or analysed using FEM analysis.

The process enables the speed-up of product development processes of large structural components aiming at lightweight designs. Key beneficiaries are small companies which may not be able to afford well-staffed analysis and design departments. By reducing the manual effort as well as the know how required to interpret topology optimizations, the proposed tool enables small companies to productively incorporate topology optimizations in their development processes, improving their products in the end.

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