From: Xu Guo, Hai Huang: Advances in Structural and Multidisciplinary Optimization, Dalian University of Technology Press, 2020, Proceeding of the World Congress of Structural and Multidisciplinary Optimization, 2019, Beijing, pp. 177-182

On a Physics-based Reconstruction Algorithm for Generating Clean Parametric Native CAD-Models from Density-based Topology Optimization Results

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Abstract

The paper describes a physics-based reconstruction algorithm for the generation of clean, parametric, beam-like native CAD structures from density-based topology optimization (TO) results. As an algorithmic key element in this process, a physics-based stress tensor criteria available from density-based TO results is used in the automated TO result interpretation process. In the fully automated reconstruction process to clean parametric native CAD-models, this criterion enables a fully automated clustering of density-based TO results based on the local stress tensor values. The complete process chain of algorithms works with almost any arbitrary topology optimization algorithm capable to return a stress density field and the stress tensor field distribution for further processing. For the reconstruction algorithm the use of a central data model for both the definition of the TO model and the reconstruction of the TO result is proposed. This allows to solve the topology interpretation problem using a model-based approach. The resulting internal model of the identified parametric topology of the beam-like structures is finally converted into a clean, parametric CAD-model in the native format of a target CAD-kernel using model-to-text transformations.

Keywords: *density-based topology optimization, reconstruction of topology optimization, native CAD models, parametric CAD-models*

1. Introduction

Structural optimization is a development tool often used for idea generation of structural concepts in the early phases of the product design process, where a structural engineer may still enjoy a relatively high amount of freedom. At the beginning of the design process, topology optimization may be applied as the design is not yet defined and the freedom can be used to find an idea for a low-weight structural design. Here, the process of structural topology optimization (TO) usually starts with a design problem consisting of a design space definition, loads and constraints. Based on a TO, a structural design proposal is derived and has to be reconstructed. Based on the geometrical complexity of the TO result, the manual reconstruction can be a tedious task. Having defined the geometry manually, mostly a validation step is included to ensure product functionality. If the structure cannot be manufactured or if a requirement changes, manual rework is necessary. These iteration cycles are time-expensive tasks.

Economic reasons lead to the goal of fully automating this process of finding the optimal structural solution for a set of requirements. In this context, the authors propose firstly to use a central data model for the integration of all domains involved [1], and secondly to use a physics-based clustering criterion for the algorithm for the design interpretation of the topology optimization result, see Figure 1.

In contrast to the described manual process, we propose a completely automated process chain of algorithms which uses a central data model for both the definition of the TO model and the reconstruction of the TO result. Starting with a central data model, which is based on the requirements and displayed in Figure 1, the design problem can be altered at any point in the product development process with no additional effort. The design problem definition is model-based and a TO model can be derived automatically. This process was recently published in [1].

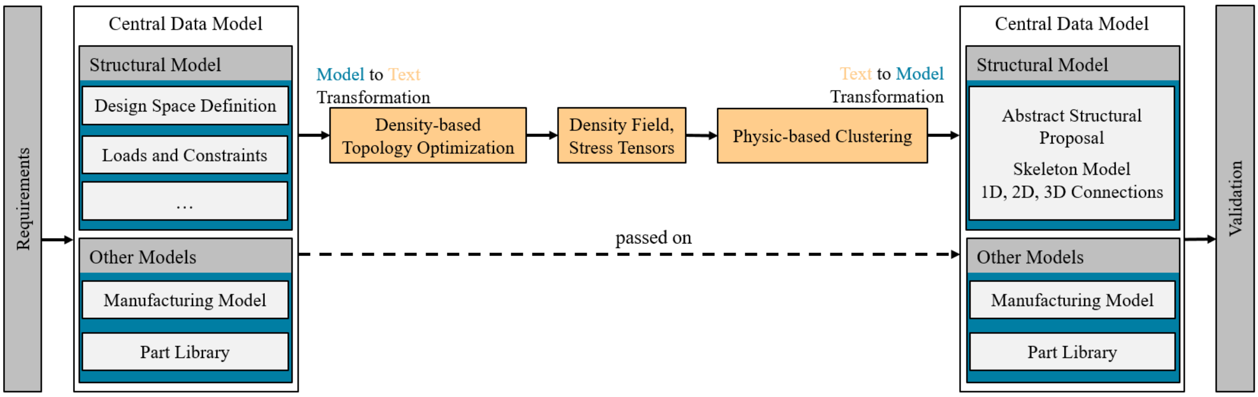

Figure 1. Proposed Process for Topology Optimization Interpretation

The work described in this paper focuses on the detailed description of the physics-based clustering criterion and process result, which is the basis for automated interpretation of TO results and the generation of a clean parametric native CAD-model thereof later on.

The paper is structured as follows: First, the reconstruction process is described. This description is made with a 2D example. That the process also works in 3D is shown with a corresponding example. The paper closes with a discussion, conclusion and an outlook.

2. Physics-based Clustering Algorithm for TO results

According to [2], the gap between TO models and CAD models is a complex challenge and its closing represents an open research problem. TO results cannot be used directly for further design processing steps such as the design of functional integration or conventional manufacturing. In order to close the gap between TO results and the desired clean and parametric CAD geometry for conventional manufacturing, the TO result is clustered into coherent areas which later can be identified and interpreted as beams and linking zones between them. This section illustrates the clustering algorithm with the example of a “C”-clip under a single load case (see Figure 3 (left)) and with the following model parameters: Meshsize of 10 mm shell elements with a thickness of 50 mm, Objective: Min(Compliance) with a volume fraction of 0.3, minimum member size of 50 mm is activated.

Looking at the results of a density-driven TO, a threshold value has to be chosen. All elements, which have a higher density as the chosen threshold are considered as solid material. All other elements are seen as void material. This returns an element set which itself is a subset of the design space. The element set based on the iso value is first clustered into beam and linking zones using the dimensionality of the stress tensor of each element. All beam elements are then clustered into coherent tension and compression zones and finally clustered based on a histogram, which uses the direction of the dominant stress. The linking zones are refined afterwards and the geometry reconstruction process starts. The clustering process is displayed in Figure 2 and described in more detail below.

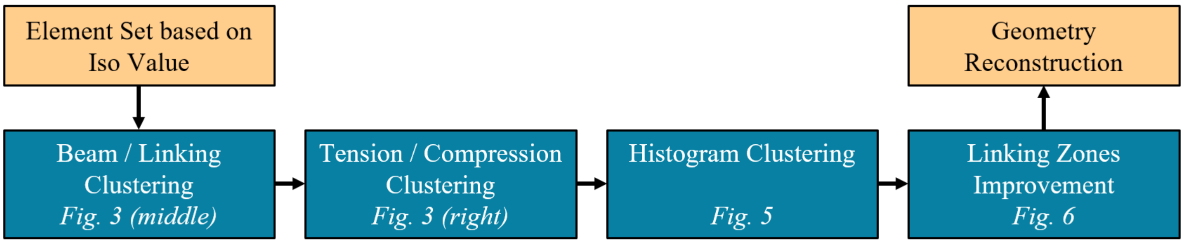

Figure 2. Overview of Clustering process described below.

For the Beam / Linking clustering, the approach is to look at the stress tensor of each element and identify the principal stresses. We search for beam-like structures by defining an element to be a beam-element, if the absolute of one of the principal stresses is at least three times greater than the other two principal stresses. We denote the direction of the dominant stress as the principal stress direction below. On the other hand, if two of the three principal stresses are three times greater than the remaining stress, the assumption of a plane stress condition can be made allowing differentiating planar structures from volumetric ones. For the example shown in Figure 3, this is not necessary in principle, as it is a two-dimensional load case only. For this paper, we differentiate only between beam-like structures (with a stress criterion as stated above) and linking zone structures (which are all other remaining elements).

In the clustering process, the beam elements are separated in a tension stress zone and a compression stress zone by looking at the mean stress which can be calculated as the average of the principal stresses. The two zones are displayed in Figure 3 (right). Each of the two zones is further clustered in coherent zones. Coherent zones are found by looking at the neighbour relationships of the elements. Elements are considered to be neighbour-elements if they share at least one node. A coherent zone is a set of elements where each element can be reached from each element by neighbour relationships only.

The outcome of this clustering step is a finite number of tension beam clusters and compression beam clusters. Dividing tension cluster from compression clusters works especially well for TO results. Minimizing the compliance (i.e. maximizing the stiffness) of the structure avoids bending structures as they are not fully stressed.

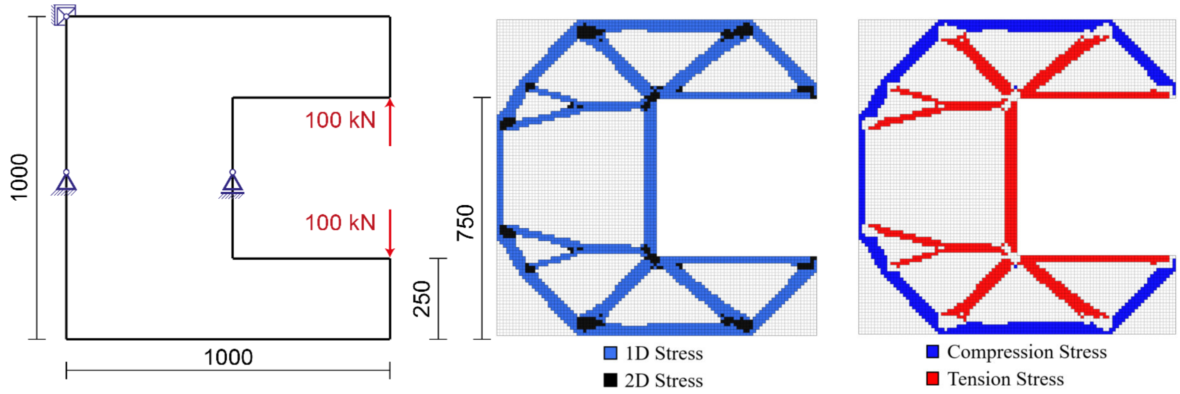

Figure 3 Load definition of the 2D example (left); differentiate between one dimensional stress state and two/three dimensional stress state (middle); differentiate between compression and tension stress zones

In order to identify the different beams, a histogram idea on stress direction is applied. We propose to use a unit sphere on which all possible stress directions are drawn. The sphere is divided into sections, called bins. The number of elements with stress directions pointing in this bin is calculated for each bin. This results in a histogram. As most elements tend to have similar principal stress direction within a beam, the histogram is supposed to possess distinct maxima. Determining all maxima on this histogram reveals the number and location of the cluster centroids. Maxima are considered as being bins which have higher counts on elements than the neighbour bins. As a final processing step, all elements are assigned to their closest maximum. Depending on the bin size, it might be necessary to combine two maxima together if they are very close. This can be accomplished with a threshold value (e.g. combine all maxima with a delta in principal stress direction angle smaller than 1 degree).

Applying the described histogram clustering process on the example, consider the outer part of the clip structure in Figure 3. From the clustering process described above, the compression cluster displayed in blue has a high variance in principal stress direction. For a two dimensional load case the stress directions are drawn on a unit circle rather than a unit sphere. The unit circle is divided hereby into bins of 5 degrees shown in Figure 4.

This histogram clustering process is applied on each of the coherent tension and compression zones and is the final clustering step for the beam zones as it results in distinct beams, as shown in Figure 5 (left).

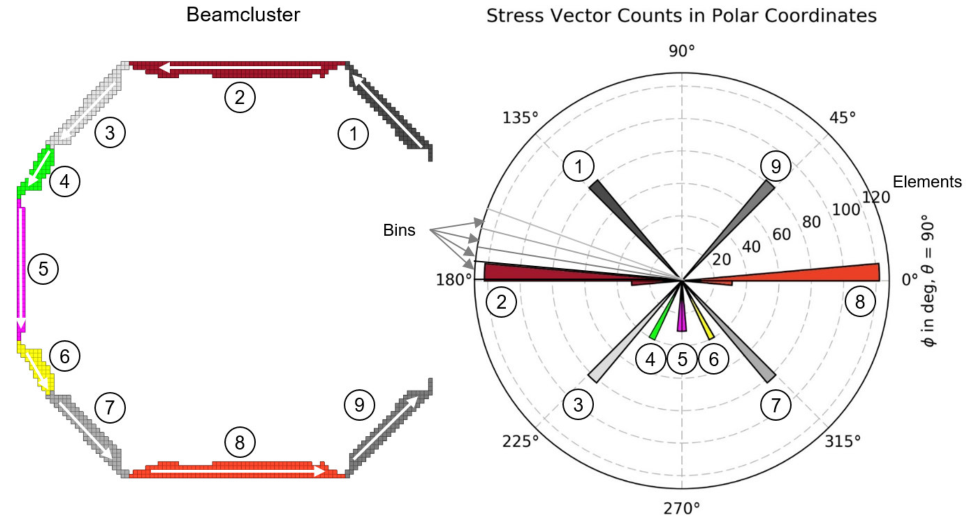

Figure 4. Result of this particular clustering with histogram of the major stress direction with cluster indication

Finally, the linking zones are refined and extended as it is shown in Figure 5 (right).

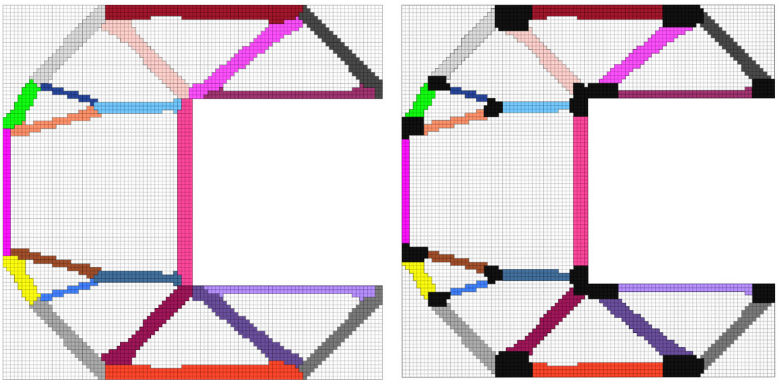

Figure 5. Third step of the clustering process: Histogram Clustering Result (left); result of the Clustering Process with extended Linking Zones (right)

The complete clustering process is summarized and displayed in Figure 6.

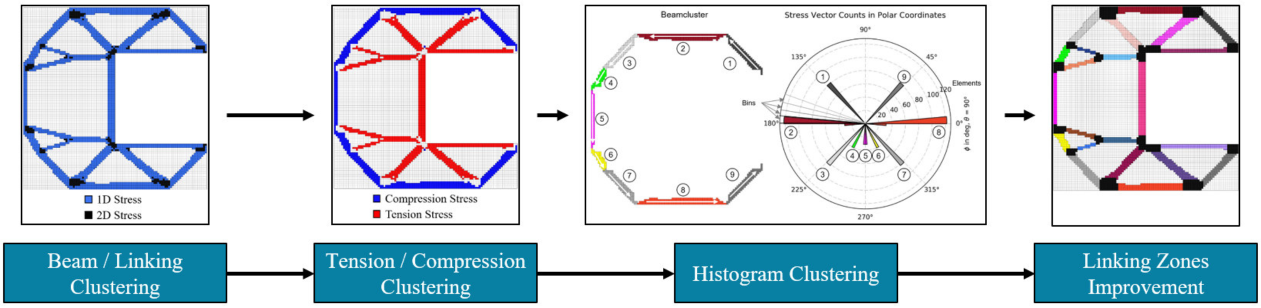

Figure 6. Complete Clustering Process

Based on this clustering result, the abstract representation can be extracted which forms the basis for creating a clean, parametric CAD model.

For all beam structures, start and end point are used to define the length and direction of the profiles. The cross-section is assumed to be constant and is taken from the elements of the TO results. The linking zones, on the other hand, are generated by placing a sphere into the centre and adjusting the profiles to the connected beam elements.
All topological information for the geometry definition is taken from the clustering process with an abstract graph, which is shown in Figure 7 (left). Choosing circular profile cross-sections, a geometry model like the one displayed in the same Figure (middle) can be generated automatically in different CAD kernels like CATIA (from Dassault Systems) or OpenCascade (from OPEN CASCADE). Using model-based transformation techniques, the clean parametric CAD-model can be generated from the abstract geometry description [3] by means of model-to-text transformations. The choice of a target CAD-kernel is arbitrary and with a given interface any CAD kernel can be used for generating the model [3]. Note that the beam diameters do vary and do depend on the TO result.

It is also possible to generate a 1D FEM model for validation reasons. It is displayed in Figure 7 (right) and shows a maximum displacement of 0.7 mm under load.

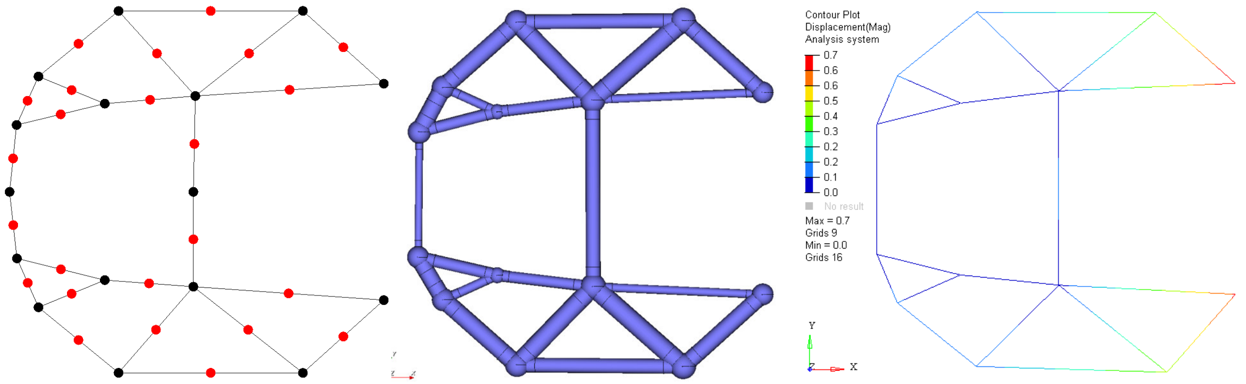

Figure 7. Abstract topology representation with a graph (left); clean parametric CAD model with cylinder extrusion profiles and spherical structural links (middle); validation displacement plot of 1D FEM model (right)

Shown below in Figure 8, the very same clustering process is applied to a three-dimensional example.

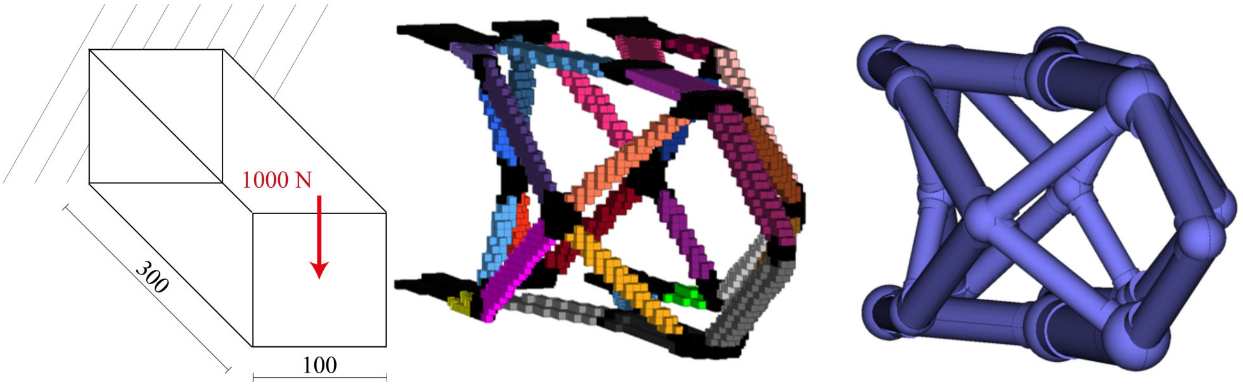

Figure 8. Three-dimensional cantilever beam problem. Design space definition (left); clustering result (middle); generated parametric CAD model (right)

3. Discussion

We proposed a physics-based clustering algorithm for beam-like TO results. The main difference to other interpretation strategies of TO results (e.g. [2]) is its physics-based nature. Working with the stress information already available from TO results is consistent with the physics of the problem rather than using the geometric information of the TO results and to do a purely geometric interpretation of the result. The second new aspect of the proposed algorithm is the definition of a spherical histogram idea on stress directions. Comparing our algorithm to e.g. the *k-means* algorithm, the main advantage is that the number of clusters is known prior to clustering. The *k-means* algorithm lacks at this point and produces poor results when the number of clusters is determined with state of the art methods like the *knee curve*.

The example shown in this paper has a single load step. The question how to treat multiple load steps and therefore multiple major stress directions are valid. Our analyses yielded that this limitation can be overcome by taking the envelope of the *van Mises* stress value for each element and take the stress tensor respectively for the clustering process. A short-term goal is the evaluation of the found geometry results and to take this as the basis for integrating size and parametric shape optimization procedures as discussed below in section 4. Another point to be considered in the future is the robustness of the proposed algorithm.

4. Conclusions and Outlook

In this paper the gap between TO and parametric CAD-geometry design has been closed by the presentation a new, physics-based multi-step clustering algorithm. This algorithm clusters beam-like TO results into coherent zones of beams and links. At the heart of the algorithm, a histogram based clustering is conducted on the maximum principal stress vectors. The clustering result is transferred into a graph, which can be used for geometry reconstruction.

We showed several geometry reconstruction possibilities, including a hybrid design, where only linking zones are designed for additive manufacturing, whereas beam structures are assumed to be standardized parts, available for (more cost-sensitive) purchasing. For future research possibilities, we look to integrate shape and sizing optimization.

As the topology of the TO results can be clustered accurately, the shape is not the same as given by the TO results. Integrating shape optimization to further improve the design is a short-term goal. Further, we look to integrate different design principles, which can be defined within the central data model and which the clustering algorithm uses in an intelligent way when giving design proposals.
We also would like to extend the functionality of fully automatically generating geometry based on TO results to surface-like structures as well. We see this as a more long-term goal with the proposed approach as the clustering criteria is different from the one used with beam-like structures.

5. Acknowledgements

The project „digital product life-cycle“ (ZAFH, see https://dip.reutlingen-university.de for details) is supported by a grant from the European Regional Development Fund and the Ministry of Science, Research and the Arts of Baden-Württemberg, Germany (information under: www.rwb-efre.baden-wuerttemberg.de).

6. References

1. Ramsaier M. and Stetter R. and Till M. and Rudolph S. and Schumacher A: Automatic definition of density-driven topology optimization with graph-based design languages. Proc. of the 12thWorld Congress on Structural and Multidisciplinary Optimisation, 2017, Braunschweig
2. Nana A and Cuillière JC and Francois V: Automatic reconstruction of beam structures from 3d topology optimization results. Computers & Structures 189, 2017
3. Schmidt, J. and Rudolph, S.: Graph-Based Design Languages: A Lingua Franca for Product Design Including Abstract Geometry. IEEE Computer Graphics and Applications (CG&A), September 2016, pp. 88-93.