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AUTOMATED TOPOLOGICAL CLUSTERING OF DESIGN PROPOSALS IN STRUCTURAL OPTIMISATION

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Abstract
Topology optimisation provides support in designing new components. However, the inbuilt multitude of optimisation parameters (penalty factor, etc.) as well as the finite element parameters (mesh, etc.) influences the simulation results and leads to a multitude of design proposals, which have to be evaluated manually by the product developer. Therefore, an evaluation algorithm was developed, which is able to quantitate the structural resemblance of two design proposals. By enabling a computer to generate and process both the visual compare and its result, it is possible to cluster design proposals that share the same major topology. So systematic parameter studies are simplified and this provides a deeper simulation and product understanding.
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Key Words: Evaluation Tool, Topological Clustering, Design Automation, Simulation Based Design

1. INTRODUCTION

Because of various influences like globalization or fusion of different markets and increasing competition on the world market, small and middle sized companies in particular need to show a continuously increasing ability to innovate [1]. Thus, a more effective and accelerated product development process is necessary [2].

1.1 Development process of products

Nowadays, the development process of products is mainly based on computer-aided systems. Therefore, it is often called virtual product development process, as shown in Fig. 1 [3]. Previously, to further develop technical constructions it was necessary to rely on empirical data, often causing faulty constructions. Today, computer-aided support tools help the engineer and might prevent possible errors. By integrating and implementing these simulation tools as early in the product development process as possible, development times, costs, etc. are reduced [2, 4]. However, in order to utilize the tools efficiently, an adequately trained product developer is necessary.

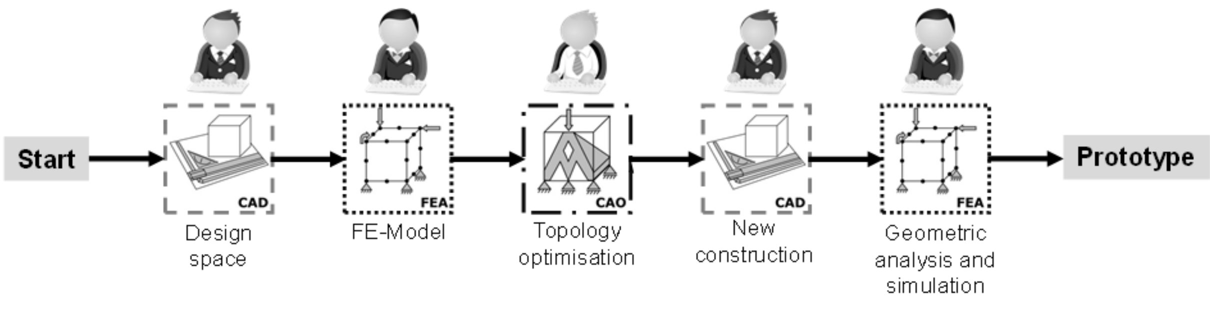


Figure 1: Schematic view of the virtual product development process [3].

In the case of Finite Element Analysis (FEA), necessary model information (component geometry, magnitude of forces, etc.) needs to be known. This is why such a tool can hardly be used during conception phase because many important facts have not been identified yet. Because of this it is not possible to change the primary geometry of the product without expending significant amounts of money and time. To solve this problem, topology optimisation can be used as an additional method to detect possible design solutions. By adding such simulation tools, the virtual process of product development is no longer sheer analysis but now extends to synthesis as well. This means that concept decisions no longer solely rely on the engineer's experience [5, 6].

1.2 Structural optimisation

Topology optimisation appears as a subdomain of the structural optimisation. Eschenauer refers to it as the so called three pillar concept [7], which consists of structural analysis, optimisation model and optimisation algorithm (see Fig. 2).

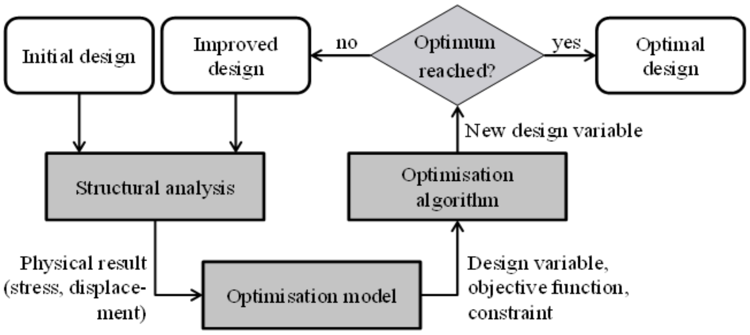


Figure 2: Three pillar concept of Eschenauer [8].

The process of structural analysis requires constraints and target functions for the optimisation model. This necessitates a calculation of the maximum stress, displacement or distortion. By using the constraints and target functions an optimisation problem is created, that can then be iteratively solved by an algorithm to achieve an optimum [9, 10]. Optimisation process of this kind is basically a question of distributing material. In order to achieve an optimised design the present material is reduced and redistributed according to bionic principals to for example maximize the stiffness [5]. Considering finite elements as design variables, they are moved or removed in order to create a 0-1-structure. The resulting structure has areas containing material (1) and areas not containing material (0) [11].

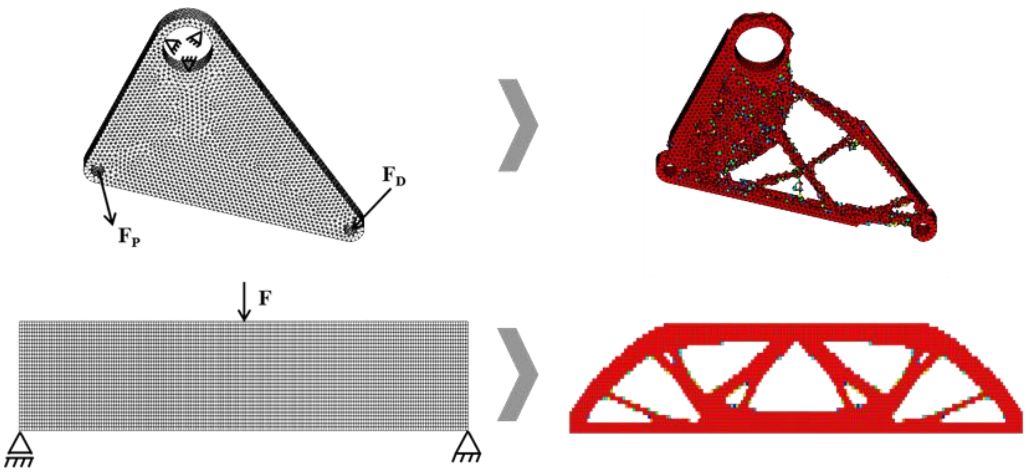


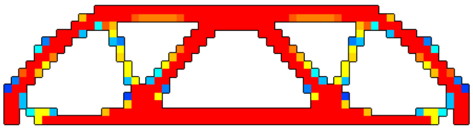
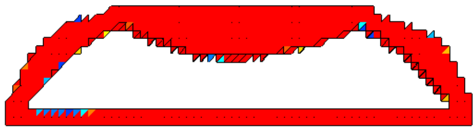
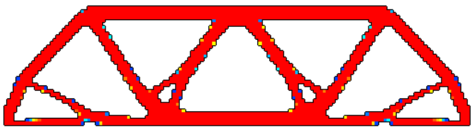
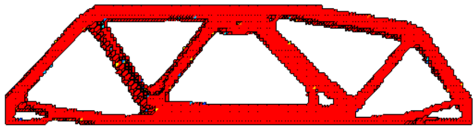
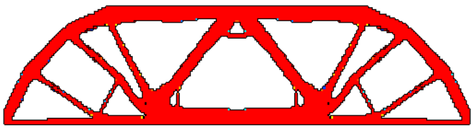
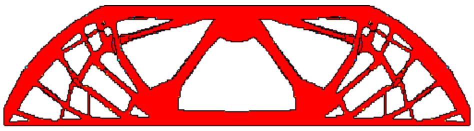
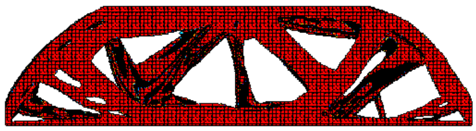
Figure 3: Design space with boundary conditions (left) and exemplary design proposal (right) of a rocker mounting (top) and the Messerschmitt-Bölkow-Blohm-beam (bottom) [8, 12].

Fig. 3 shows this optimisation process and the resulting 0-1-structure for two examples which are chosen due to their nearly 2D characteristic to enable a visual evaluation: the rocker mounting (see Fig. 3 top) and the Messerschmitt-Bölkow-Blohm-beam (MBB-beam) by Olhoff [12] (see Fig. 3 bottom).

2. THE PROBLEMS OF STRUCTURAL OPTIMISATION

There are still some problems that impede the total automatization of the virtual optimisation like the necessary smoothing of the jagged structure and the inbuilt multitude of optimisation parameters (e.g. the optimisation algorithm and penalty factor) with their influence on the simulation result [13, 14]. The available adjustment possibilities brought by FEA (boundary conditions, meshing parameters, solvers, etc.) add extra complexity and lead to a multitude of design proposals that need to be evaluated critically by the product developer [15, 16]. This effect can be seen as an example in Table I which shows the influence of discretization on the optimisation result of a MBB-beam.

Table I: Influence of the discretization on the optimisation result of a MBB-beam [8].

Degrees of freedom	Optimisation result	
	Linear hexahedrons	Linear tetrahedrons
6048		
52326		
227835		
776055		

Due to the prevalent sensitivity, variation of other above-mentioned FE and optimisation parameters yields even more design proposals. Due to the sheer volume a manual evaluation, until now done visually, is simply not feasible [17, 18]. This makes a realisation of topology optimisation and systematic investigation of different factors of influence economically impossible. But just this need of systematic studies was mentioned as one of three future challenges of topology optimization for industrial application [19]. So, the aim is to aid the expensive and error-prone evaluation of design proposals by computer systems that only the resulting major topologies has to be considered by the product developer.

3. EVALUATION TOOL FOR DESIGN PROPOSALS

While keeping in mind that the optimisation process does not account for manufacturability, similar design proposals can be identified. Thereby, it is the difficulty to detect evaluation parameters which score the structural conformity. In FEA one can use the maximum deflection as comparison criteria, but due to the nature of a 0-1-structure in topology optimisation, there are a variety of design proposals that yield similar values of any aggregated variable such as the sum of compliance [5, 20, 21]. Such a loss of local structure information is unacceptable, so the design proposals cannot be evaluated by simply comparing scalar values. Up until now, the comparison of design proposals has to be run visually by the developer.

3.1 Procedure of the evaluation algorithm

To evaluate design proposals with the aid of a computer, a local investigation and comparison of design variables is necessary. An evaluation algorithm was developed for this purpose, which is demonstrated in Fig. 4. For a better overview the algorithm is explained using an abstract example, consisting of two design proposals A (DPA) and B (DPB). The differences at the design proposals result from different meshes.

Each finite element centre (●) from DPA's mesh is projected onto DPB, with a target value being calculated. In the following, this is compared to the actual value in design proposal A, in this case a value of 1.0. The target value is calculated using the finite element in DPB nearest to the centre of DPA's projected element (d_{min}). The different meshes necessitate an interpolation of the considered design variables of DPB, which is done by inverse distance weighting.

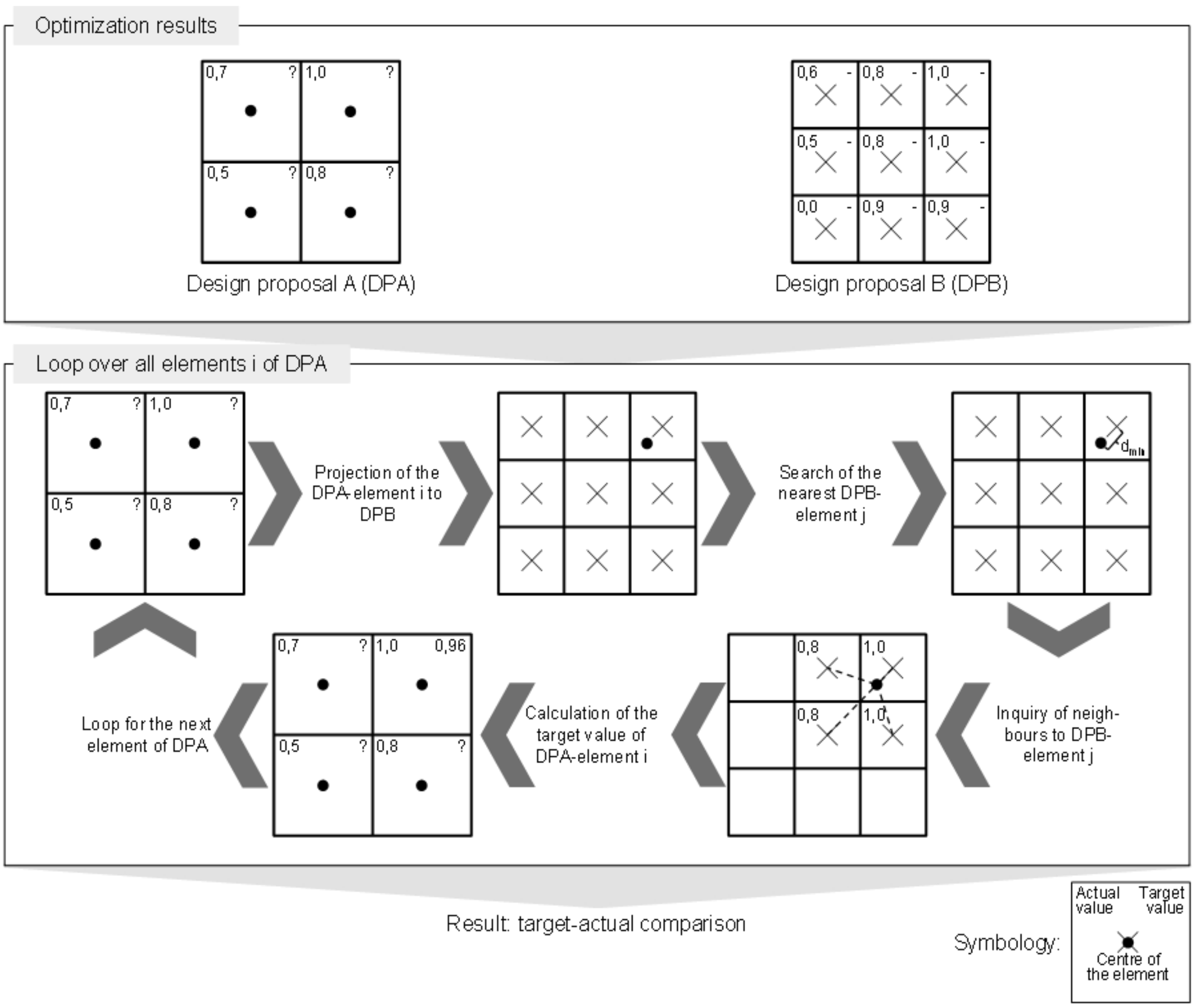


Figure 4: Evaluation algorithm for comparing design proposal A and B.

The principle of spatial correlation provides the basis for this method by providing that the similarity of an unknown value v to the known values v_j drops with the euclidean distance d_j [22, 23]:

$$v = \frac{\sum_{j=1}^{n} \frac{1}{d_j^p} v_j}{\sum_{j=1}^{n} \frac{1}{d_j^p}} \tag{1}$$

The exponent p thereby controls the weight of the distance:

- $p = 0$: Arithmetic mean equals target value (no influence),
- $p > 0$: Less influence by further elements, whereas by increasing p drops the influence of distant values.

At our investigations an exponent value of 2, which is widely used in geostatistics, yields reliable approximations for this object [22, 23]. However, because the local method of interpolation implies the neglect of distant values, the actual influence is limited. This is due to the fact that only adjacent elements are considered, which by nature are in close spatial proximity to the searched value v.

3.2 Result processing

Using the target value (here: 0.96) calculated with Eq. (1), a target-actual comparison can be made to expose differences between the two design proposals. An accumulated histogram reflecting the relative amount of occurrences of a finite element (y-axis) for each category of the absolute target-actual comparison (x-axis) is a useful tool to recognize similar design proposals. While the upper histogram in Fig. 5 shows two different topologies where nearly 50 % of the elements vary in the value of their design variable by more than 0.8 to the target value, the lower histogram indicates that 90 % of elements have a smaller variation than 0.2, suggesting similar topologies.

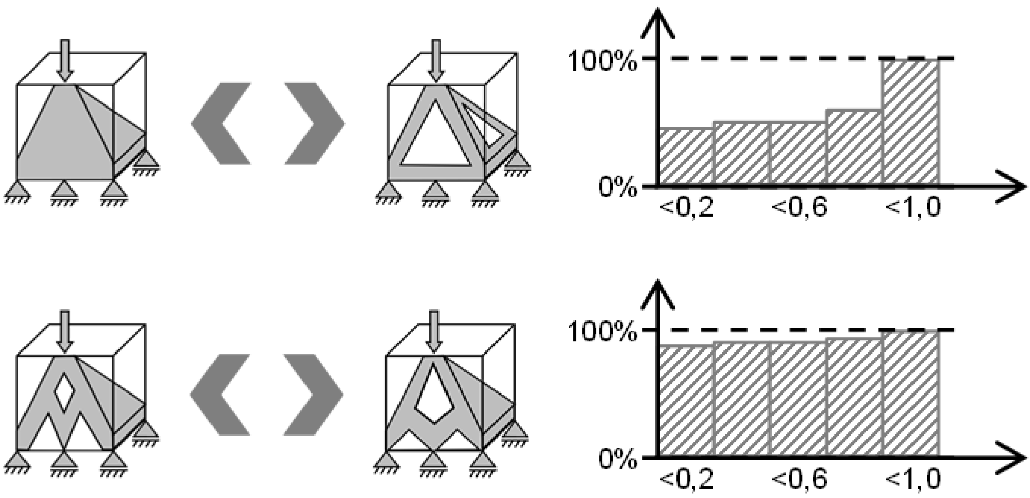


Figure 5: Topological comparison of two design proposals by accumulated histograms.

3.3 Simulation example: MBB-beam

A topological evaluation tool can be validated by a visual plausibility check. The procedure can be demonstrated by means of an example with nearly identical design proposals of the MBB-beam, which resulted from a mesh with linear (see Fig. 6, top left) and quadratic (see Fig. 6, top right) hexahedrons.

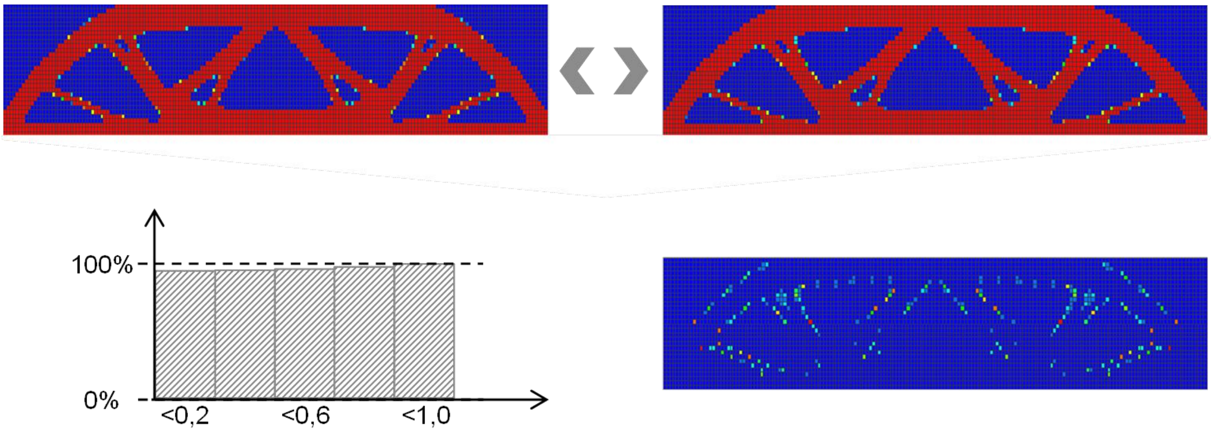


Figure 6: Comparison of two nearly identical design proposals of a MBB-beam (top left: linear hexahedrons; top right: quadratic hexahedrons) with an accumulated histogram (bottom left) and the values of the target-actual comparison for every finite element (bottom right).

The two shown design proposals, consisting of the 0-1-structure (grey = 1 and black = 0) are very similar. This can be concluded from both, the histogram at the lower left and the figure at the lower right, which shows the deviation of the design variable explicitly for each element. Merely in areas of transition from 0- to 1-structure deviations occur, which do not affect the major topology of the design proposal. The remaining areas, which are black and consequently have no difference in the design variable, confirm the similarity. However, there is no clear boundary to determine what variation values warrant two design proposals to be considered as similar.

4. LIMIT VALUE FOR THE TOPOLOGICAL SIMILARITY AND AUTOMATED TOPOLOGICAL CLUSTERING

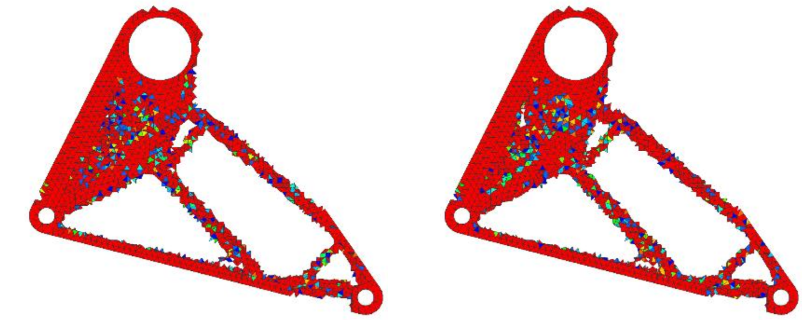
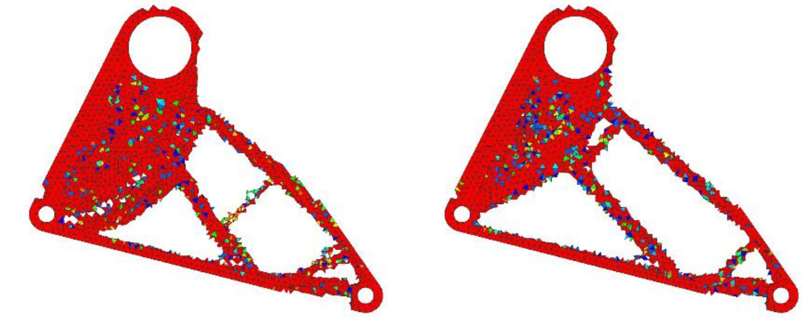
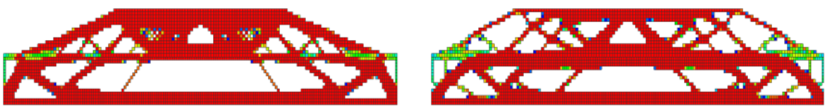
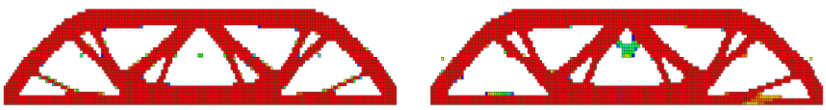
The above mentioned example represents thereby an extreme case due to the obvious similarity of both design proposals which can be seen easily. However, for the complete automation of the evaluation process a defined limit value is necessary for the decision whether two design proposals are similar or not. Starting from this limit value the algorithm evaluates two design proposals as sufficiently similar and assigns them to a major topology. This crucial question of which numerical value should be chosen cannot be answered exactly. This is why this parameter can be selected by the product developer. Nevertheless, the empirical survey in the following provides a recommendation for the limit value.

For that purpose, 55 product developers, which are familiar with the topics "simulation" and "topology optimisation", were consulted. The attendees were presented 53 pairs of design proposals of the MBB-beam and the rocker mounting (see Fig. 3). The task was to determine at one's own discretion whether the particular pair should be clustered to a major topology or not. As the algorithm is supposed to support engineers by categorizing similar design proposals which result of topology optimisation, it is now important to detect the human understanding of whether a design is similar to another or not. Four exemplary evaluations are shown in Table II.

The table contains the percentage amount of participants who evaluated both design proposals as similar and the calculated percentage amount of finite elements, which have a smaller deviation value than 0.2.

Considering the first example the survey participants (100.0 % agreement) as well as the evaluation tool (96.8 % of the finite elements have a less aberration than 0.2) confirm the topological similarity. At the same time, the big differences of the design proposals of example No. 4 were affirmed because 92.73 % percent of the survey participants as well as the evaluation tool specified both as dissimilar. So, the design proposals of example No. 4 may not be clustered to one major topology.

Table II: Exemplary design proposals and their results at the survey and the evaluation tool regarding their individual topological similarity.

No.	Design proposals	Result [%]	
		Survey value	Evaluation tool
1		100.00	96.80
2		54.55	90.97
3		78.18	84.00
4		7.27	78.91

The survey as well as the computer-aided evaluation was performed for all 53 examples. The results are shown in Fig. 7. The percentage amount of finite elements with a smaller variation than 0.2 calculated by the developed algorithm is plotted on the x-axis, whereas the percentage amount of participants who evaluated both design proposals as similar is plotted on the y-axis. According to this, example No. 1 appears in the upper right corner of the diagram because all survey participants confirmed the similarity as well as the algorithm determined a large number of related elements. The quite dissimilar example No. 4 is located in the lower left area, respectively.

It can be seen that the results which are dependent on the own experiences of the participants correlate very well with the results of the developed evaluation tool. Only for the area between 85 % and 95 % of finite elements with a smaller variation than 0.2 (on the x-axis), no clear allocation could be obtained. As an example of this, the design proposal pair No. 2 can be consulted. Obviously, this pair was very difficult to evaluate by the survey participants. Half of the participants declared the pair No. 2 as similar, the other half as dissimilar. The reason for this unclear vote is the small differences at the thin braces which cause a visual mismatch. However, the small width of the braces might be neglected at the later manufacturing.

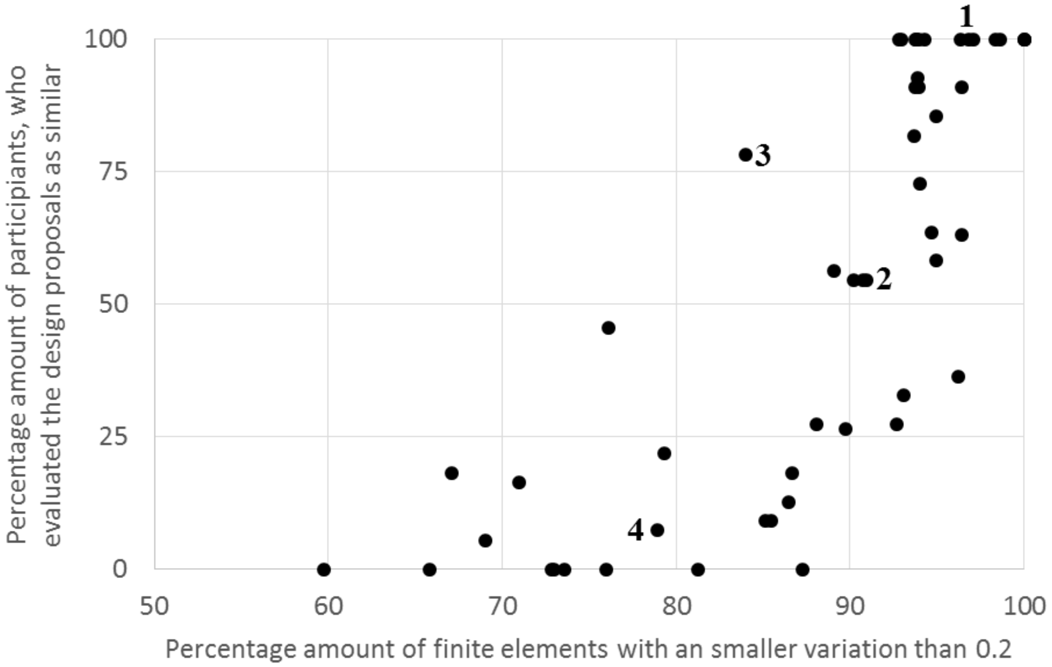


Figure 7: Results of the survey (numbers with regard to Table II) to determine a limit value for the topological similarity.

At this point, the individual experience of a participant influences his decision significantly because one might consider the design proposal with or without some thoughts on manufacturability. Due to this, example No. 2 and others with similar algorithm valuations (about 90 % on x-axis) could not obtain a clear allocation within the survey. So, this limit value is recommended for product developers, whereby unique topologies are assigned correctly and for debatable examples a good compromise can be found.

A special position is represented by both results at the upper left area of the diagram. Example No. 3 shows one of these points. Due to the thinly truss structure within the MBB-beam, a visual evaluation by the product developer is extremely difficult. At first sight, both design proposals seem to be very similar. This is why the high survey result could be achieved. However, the algorithm also compares the exact position of the individual trusses and determines therefore only a match of 84 % of the finite elements with a deviation smaller than 0.2. Thus, the evaluation tool can consequently compare more complex structures (including undercuts, cavernous structures, etc.) reliably, which cannot be evaluated efficiently by a product developer.

This characteristic value for the histogram enables us to quantify the topological similarity of two design proposals. Both the visual comparison and its result can be generated and processed by a computer, which creates the possibility of automating this expensive process. Building on this computer-aided, topological evaluation tool for two design proposals, the product developer is able to perform systematic variations of all input parameters and only consider the relevant major topologies of all design proposals, instead of hundreds of mostly similar ones. This can be achieved by an automated check of all optimisation results for topological similarities and consequently condensing of the matching ones (see Fig. 8).

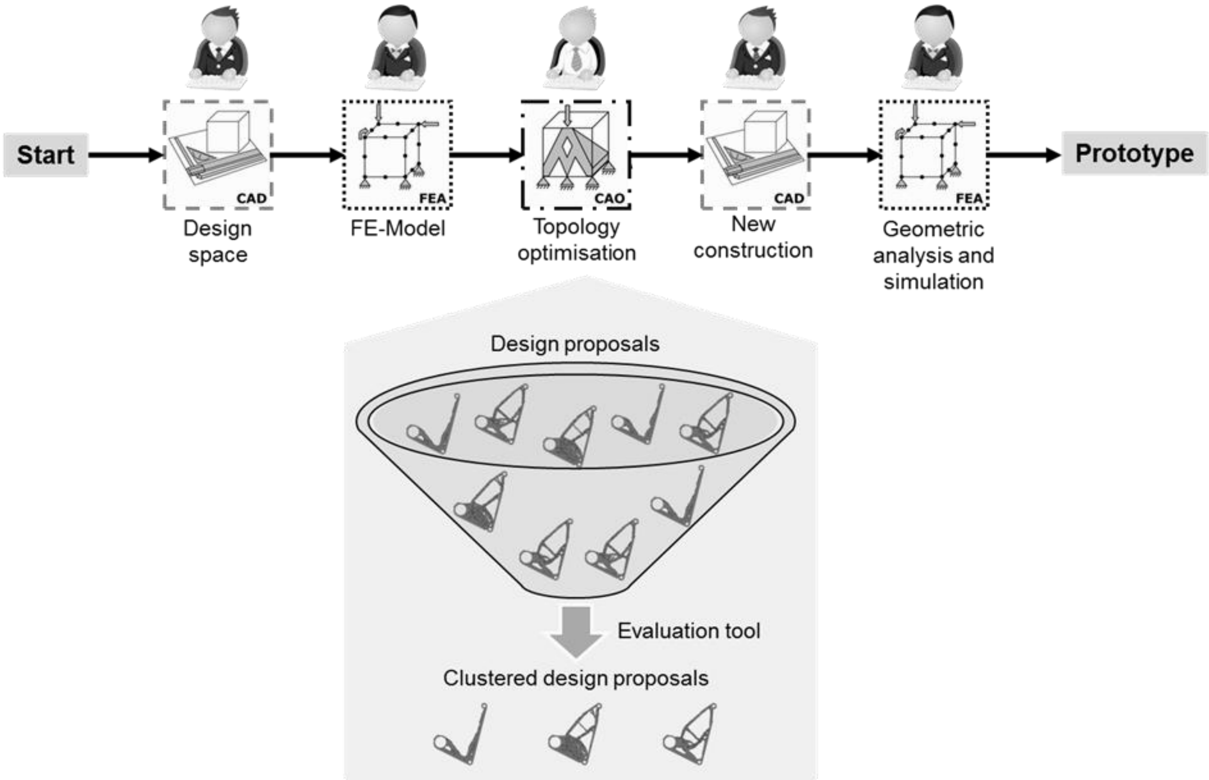


Figure 8: Virtual product development process with integrated topological clustering of design proposals.

5. CONCLUSION

Topology optimisation integrated in the product development process supports the product developer by providing a design proposal for reconstruction of the part. Setting the simulation parameters however requires profound specialized knowledge for both optimisation and FEA. Commonly used variations in relevant settings lead to a multitude of design proposals, which have to be culled manually by visual comparison. Therefore, a support tool was developed to simplify this kind of systematic studies by running a computer-aided evaluation of two design proposal's topological resemblance. As result the product developer receives instead of a multitude of design proposals only a few, which represent all occurred topologies. Thus, the evaluation tool was calibrated by the experience of surveyed product developer. So, the algorithm can provide designers with deeper simulation and product understanding and enables them to integrate optimisation in the virtual product development process.

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