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Future challenges for topology optimization for the usage in automotive lightweight design technologies

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1. Abstract

Nowadays the development of mechanical components is driven by ambitious targets. Engineers have to fulfill technical requirements simultaneously under the restrictions of minimized costs and reduced weight for mechanical components. Accordingly in the last years newly developed and tested optimization methods have been integrated in the development processes of industrial companies. Today, especially topology optimization methods are gaining in importance and are often used for the first design proposal of casting parts.

However, these design proposals must be interpreted and transferred to CAD-models by design engineers and in later development phases manufacturing aspects must be considered. Both steps need more development time and normally material must be added to the design ideas. Beside castings parts, topology optimization is only a little help for the design of sheet structures, because framework structures are the result. Also crash and acoustic requirements cannot be completely supported by optimization methods.

Beginning with the current situation four challenges for further work can be formulated. First the technical aspects like crashworthiness and acoustic requirements should be implemented into the topology optimization. The second future path focus on sheet structures and hybrid parts. With new manufacturing rules, the result of the topology optimization should only consist of thin and plane orientated material. As an extension, structures with more than one sheet should be possible in the future. The costs of needed welding seams must be considered. The third challenge is the integration of manufacturing simulation. By including a casting simulation for example, each iteration of a topology optimization can be analyzed to the castability. By modifications of the design, beside the mechanical needs also casting aspects will be recognized.

The last future path treats a continuous and integrated development process. For this target, the CAE description of the topology results must be smoothed and automatically transferred to CAD models, which fulfills the design methodology in order to allow easy modifications.

2. Keywords: Topology optimization, integrated casting simulation, multimaterial optimization, sheet structures, CAE2CAD process

3. Introduction

Today several approaches are in use for topology optimizations. The starting point for FEM based topology optimization can be found in literature in [1]. Bendsøe introduced his homogenization method first [2]. Parallel to the homogenization method, Bendsøe presented the SIMP approach (Solid Isotropic Microstructure with Penalization) [3]. This method gained popularity because other researchers applied it to their work [4]. Today the SIMP approach is a standard method for topology optimizations. For example, the commercial tool Tosca® from FE-Design [5] is based on SIMP. SIMP uses the element densities as continuous design variables. The coupled stiffness values of the elements transfer the modifications of the optimization to the structure results. At the end of each topology optimization run, a discrete distribution of material for the interpretation of the results is needed. For this reason, the SIMP approach penalizes intermediate density values using a penalization factor to assign lower stiffness values to these elements [13]. SIMP is combined with gradient algorithms, e.g. the method of moving asymptotes [7].

Since 1992 two other important approaches have been developed and published: ESO/BESO and the SKO method. The Evolutionary Structural Optimization (ESO) is focused to remove unnecessary material from too conservatively designed parts [8]. For ESO, it is only possible to remove material. A binary element modeling is in use in comparison to SIMP [9]. To enable material growth, Querin introduced the Additive Evolutionary Structural Optimization method (AESO) [10]. AESO adds material to areas in order to improve the structure. The combination of ESO and AESO leads to the Bidirectional Evolutionary Structural Optimization [BESO] method [8, 9, 12]. The main idea behind ESO, AESO and BESO is to remove lowly stressed elements and adding material to higher stressed regions. To designate these elements, a so called "reference level" is defined. Elements below the reference level are removed from the structure. In the surrounding of elements with higher stresses then the reference level, material is added. During the optimization this level is adapted to the optimization progress. BESO uses here - depending on the individual approaches - direct, gradient or interpolated information about material properties to change the structure [9]. Due to these facts, for ESO/BESO the compliance-volume product can be assumed as an objective function [6].

The Soft Kill Option method (SKO method) was introduced by Mattheck, Baumgartner and Hartzheim in [13]. Inspired by the growth of trees and bones, the biological growth rule was formulated. In highly stressed areas material can be added and in lowly stressed areas material will be removed. Homogeneous and constant stresses should be generated especially at the surface of the structure. To change the structure, the SKO method modifies the Young Modulus of the FEM-elements as a function of the temperature. High temperature indicates high Young Modulus and low temperature causes low Young Modulus [11, 13, 14, 15].

The SIMP method in combination with gradient algorithms achieved a widely-used application in industry. The main reason for the success of the approach is the integration of manufacturing restrictions [16, 17, 18]. Without manufacturing restrictions, it is impossible in most cases to get a feasible design for real life problems. Today nearly no suggestions for the integration of manufacturing restriction for BESO and the SKO method have been published. Only for SKO a further development, called Topshape®, which offers manufacturing restrictions, has been published [19].

4. The basic approach of the topology optimization

The new approach for topology optimization is designed for industrial purposes. Taking into consideration, for engineering and daily work, the optimization focus is on the improvements of existing results instead of searching for global optima. The main targets are costs and weights of the parts. In the development of casting parts, a reduction of weight is coupled with a reduction of material costs. So it is consequent to use the weight as target function. Additional important aspects are the necessary time and costs in the development process. To achieve this and to improve the general usage, linear and nonlinear FEM analysis should be combined with the new topology optimization method. Nonlinear effects can be found for example in plastic material behavior as well as by bushings and by contact problems. Finally the last point, manufacturing requirements need to be fulfilled [20, 21].

The flow chart in figure 1 illustrates the main steps of this new topology optimization method. A step size controller calculates first a basic rate. Depending on this basic rate, the numbers of removing and adding elements are defined for the modification of structural elements. According to the added element, hotspot areas are corrected. After this correction process, the lowest stress elements depending on the reduction rate are removed. After adding and removing elements, the structure will be checked to insure it is connected: all force transmission points must be connected to the support elements. If this check fails, the controller modifies the correction and reduction rate in order to produce a feasible structure. During the heuristic steps, non-connecting elements are removed from the structure. The interface routines for the FEM solver are integrated in the optimization software. After finishing all changes and checks, the optimizer writes the solver specific input decks with all active elements and coupled nodes. After the FEM analysis, the post-processing evaluates all target functions and constraints. An interface transfers this information to the controller.

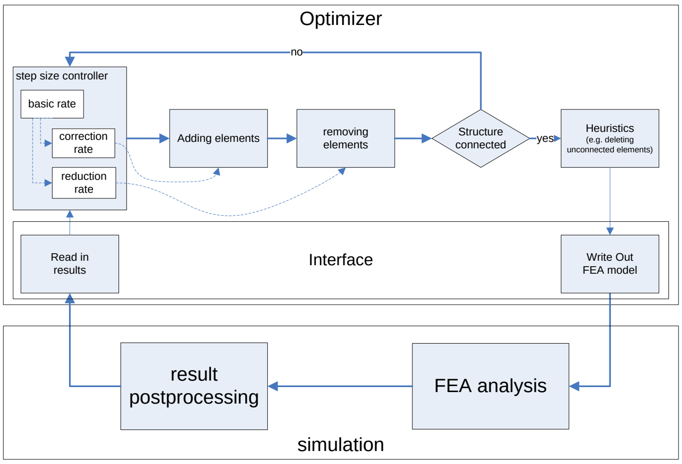


Figure 1: Flow chart of basic Topology Optimization Method

The step size controller is an important element of this new method. The main idea is to control the target function "weight" by using the progress of the constraints during the optimization. In the first step, the basic rate is modified. In a second step the reduction and correction rate are calculated depending on the basic rate to vary the structure.

The basic principle is simple. A smooth increase or decrease of the constraint function allows the removal of more elements up to the allowed maximum. In the other case, when the constraint increases, the step size is reduced, allowing only a limited number of elements to be removed but more hotspots have to be fixed. When a structure violates the maximum allowed constraint limit two times one after another interaction, the step size has to be reduced significantly: no elements are removed. In such a situation it is only allowed to add new elements to the structure. This is based on a simple heuristic from an engineer's knowledge.

Figure 2 describes the change of the basic rates dependent on the possible events and the coupling between basic rate, correction and reduction rate. High basic rates allow high reductions and less corrections will be necessary. For basic rates from 0.1 to 0, fewer reductions should be carried out. When the basic rate tends to zero, more corrections are needed. Only corrections will be done in case of a basic rate lower than zero [20].

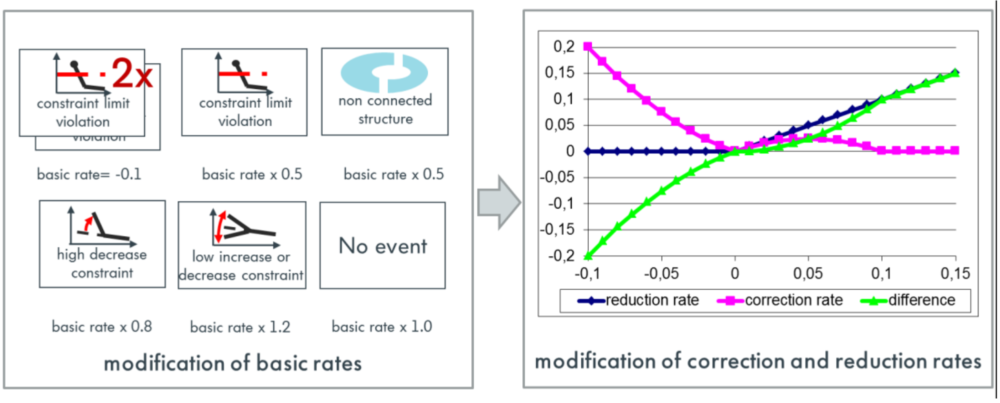


Figure 2: Step size controller modifications on the basic rates cause variations on correction and reduction rates

After the calculation of the step sizes for corrections and reductions, the structure will be modified. To avoid problems in the FEM-simulation only binary states of the material are allowed: material is solid or not available. This binary material modeling allows only a switch between both states. Similar to ESO/BESO and the biological growth rule, material will be added at the highest stress values and removed at the lowest stressed regions. In figure 3 the process is illustrated. Instead of any calculated derivations of properties to generate gradients, the stress values of the structure will be sorted in descending order. Using the step size for corrections, the neighbor elements next to the highest stress values will be added to the structure and the elements with the lowest stress values according to the reduction rate will be directly removed from the structure.

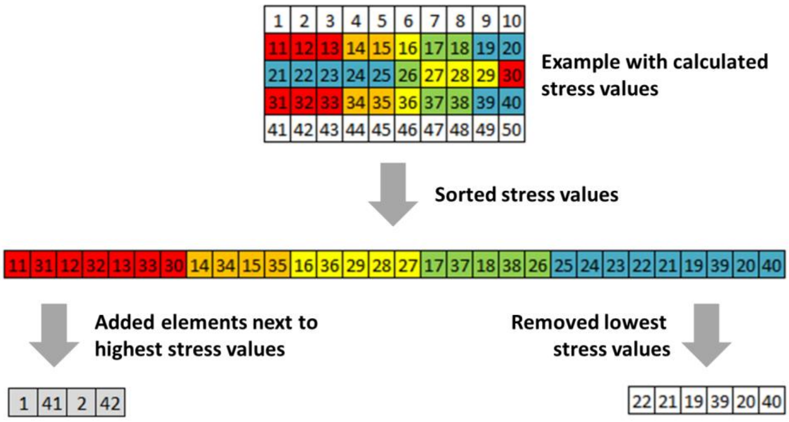


Figure 3: Modifications of an example structure by adding and removing elements by calculated stress values

The integration and implementation of the FEM simulation can be done very easily. No special material model without mayor modifications and programming work must be integrated into the code. The input deck for the FEM simulation is identical to an input deck for single simulation of a design. The interface of the optimizer writes a standard input deck of all existing elements. No removed elements will be written out. Due to this fact all FEM solvers can be used. For the simulation of the examples in this paper, Abaqus® has been used [22]. Linear, nonlinear and explicit simulations can be performed with Abaqus® [23, 24] based on the theory of the FEM [25, 26]. Using the integrated scripting procedures the stress values and constraints will be extracted to files. The optimizer starts the next optimization loop based on the information from these files.

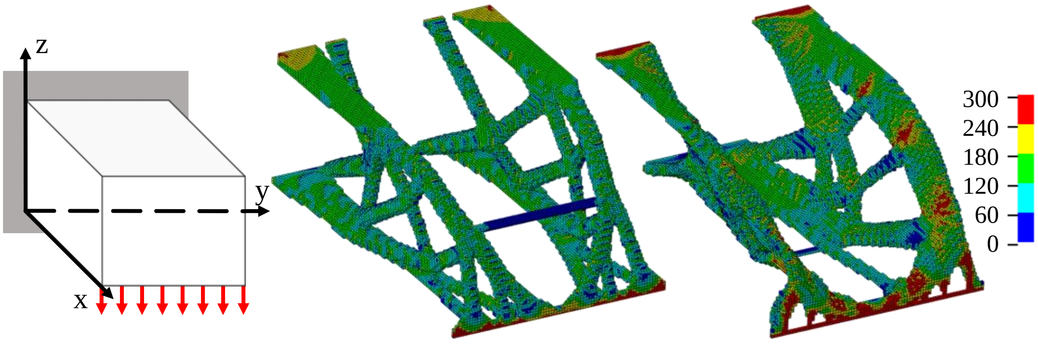
5. Necessary additional technical requirements

The topology optimization presented in chapter 4 gives the possibility to fulfill all requirements for stress constraints and misuse requirements. However the design for crashworthiness of vehicles has additional specific requirements: geometry (e.g. large displacements and rotations), boundary condition (e.g. contact) and material (e.g. plasticity, failure and strain rate dependency) [27]. Usually crash simulations are performed with Finite Element Method codes which can handle the nonlinearities by using explicit time integration. These explicit simulations are right now integrated in the topology optimization presented in chapter 4 [28]. For the further development of the approach, the optimization algorithm must be extended to handle the specific crash requirements like the existence of bifurcation points, the usage of special structural responses like energy absorption and injury criteria. The huge number of local optima make the optimization of crashworthiness structures even more complex. The conflicting goals of stiffness for structural integrity and compliance for a smooth and controlled energy absorption are important parts of the crashworthiness of vehicles.

Also acoustic requirements are not yet implemented in the current optimization tool. With regard to acoustics the research code *elementary Parallel Solver – elPaSo* developed at the *Institute for Engineering Design, Technische Universität Braunschweig* can be used to predict the acoustical parameters. The code elPaSo can run in parallel on distributed systems on multiple platforms and in multiple architectures. It is based on the Finite Element Method, the Boundary Element Method, the Scaled Boundary Finite Element Method, and hybrid numerical approaches [29, 30, 31]. The code is able to simulate a wide range of acoustical applications, from vibroacoustical sound paths to sound insulation and to the radiation of sound. Special models for viscous, viscoelastic, and poroelastic materials are already implemented just as models that describe e.g. flow-induced sound in structures.

6. New type of components and structures

At the moment, topology optimization is very popular for casting parts. If the target design should contain sheet structure or more than one material, additional extensions must be implemented. Here an improved optimization method is a topology optimization based on solid finite elements with an included manufacturing constraint for flat structures. The developed manufacturing constraint ensures that the structure does not exceed a given thickness and that the optimized sheet metal has no undercuts in order to deep draw the structure in one step. Figure 4 shows optimized structures for the same design space and load case with and without the manufacturing constraint for deep drawable sheet metals. Further information is provided by the contribution *Topology optimization considering the requirements of deep-drawn sheet metals* by Dienemann, Schumacher and Fiebig [35].



a) b) c)

Figure 4: a) Design space and loadcase b) framework structure c) flat structure without undercuts in punch direction z

To achieve even more ambitious targets in terms of weight reduction and cost savings in the development of mechanical components, new strategies are required. Hybrid components are success-promising because of the large possibilities the use of two or more material offers. Nowadays the development methods are just at the beginning and no universal process is available. To offer a first idea of the ideal distribution of the two materials, the new topology optimization is capable of handling multi-material-structures. Therefore the binary material model is expanded by distinguishing two different materials, one strong material with a high density and a weaker material with a lower density. The step size controller also differentiates between the two materials, thus the correction and reduction rates are separate for both materials. Furthermore, a new intermediate step for the modification of structural elements is introduced. Before an element of the strong material is deleted, it is converted to an element of the weaker material. If the stress value in this element is still low, it is deleted in the next iteration. A transformation from the weaker material to the stronger material is also possible, but on stress hot spots the same material is always added. The new optimization process is shown in figure 5.

An important factor on the final design of a multi-material-component is the type of joining, as an adhesive bonding leads to a different design of the joint than an interlocking structure. Both joining types are implemented in the new topology optimization.

To simulate an adhesive bond in the FE analysis, cohesive elements are added to the structure before the FE input deck is written. An algorithm searches for joints in the structure between the two elements. If a joint was found, the nodes are duplicated and a cohesive element is added. For cohesive elements with a geometric thickness the nodes are displaced by an offset, which is limited by the distortion of the connected elements. If a zero-thickness modelling is used, the coordinates for the duplicated nodes are coincident. The cohesive elements return stress values which represent the stress distribution in the adhesive layer. Hence an active design of the joint by the optimizer is possible, as the size of contact areas could be increased and load directions could be changed.

For interlocking structures, contact conditions between both materials are defined. To improve the load-bearing capacity of the joint, the structure of the contact surface could be modified or enclosing structures could be formed.

In contrast to a single material casting part, the component cost is also directly influenced by the costs of the joining process. Therefore an expansion of the cost model is suitable, which could then be used as a target function for the multi-material-optimization.

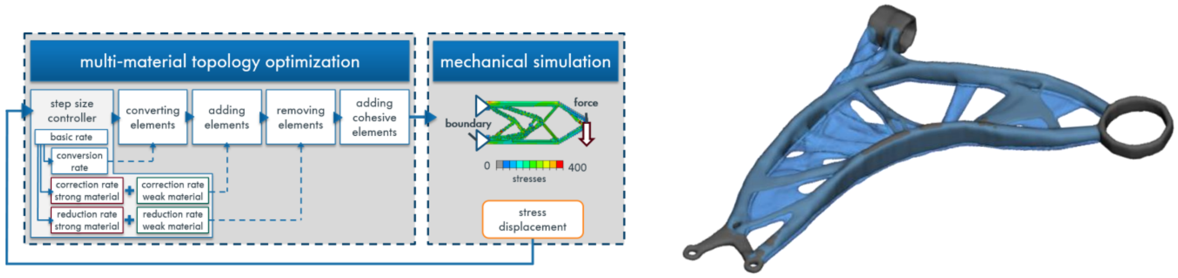


Figure 5: Topology optimization for multi-material, flowchart and exemplary optimization of a control arm

7. Integration of manufacturing simulation

Currently the topology optimization considers only the mechanical simulation results to modify the structure. Only basic rules for manufacturing restrictions, like the casting direction are integrated. Therefore, much work is necessary to optimize the castability after the first design proposals. This work can be saved and the quality of the first concept can be massively increased by the integration of a two-step-approach. First the optimization procedure is extended by more detailed manufacturing rules such as a draft angle and minimum hole and pocket sizes. Secondly a casting simulation is integrated in the topology optimization to determine the castability of the design. Figure 6 shows the new workflow of the optimization process. In each optimization loop, a casting simulation iruns parallel.

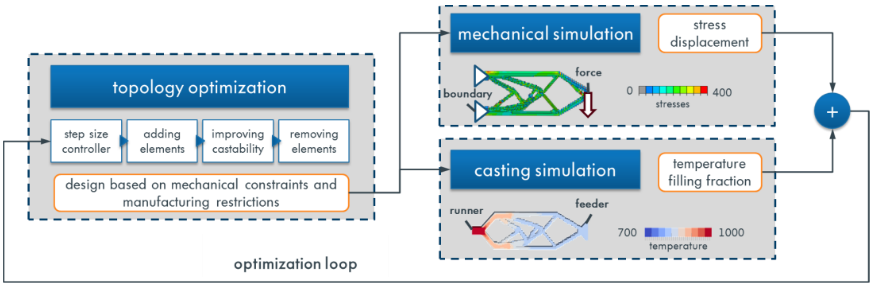


Figure 6: Topology optimization with integrated casting simulation

The results of the casting simulation are used in the optimization to improve the castability after the adding of material due to high stresses. Elements which aren't filled completely are grouped. It is assumed, that these regions are too thin or inappropriately placed to be filled properly. Depended on the visibility the elements are removed or reinforced. Figure 7 shows the compact result of this procedure. To prevent deep cuts in the structure a maximum depth mechanism is used. This whole procedure causes a violation of the structure every time elements are removed with high stresses. Because only few elements are changed in each iteration, the optimization can repair the structure in the next step and a feasible design is ensured.

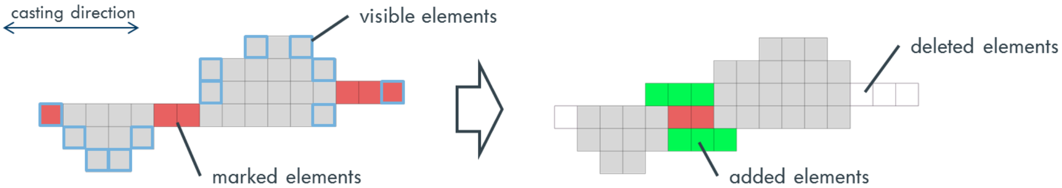


Figure 7: Changing of the structure due to not filled elements

This approach is discussed in a simple example. The target is the weight reduction. A stress restriction is used; the material of the part is an aluminium alloy. Two symmetric load cases are defined. Figure 8 shows two optimization results. The first design was generated with the basic optimization. The weight is reduced to 35.5% of the start design. The structure contains a lot of small beams and is complicated to produce. Parallel the optimization was done with an integrated casting simulation. The small beams are deleted every time they become too small to be filled. The result is a clear structure with few beams. In this case the weight is reduced to 35.3%. This is even lighter than the result of the basic optimization. Although more restrictions are used and the result is clearly different in topology and shape, a higher weight reduction can be reached.

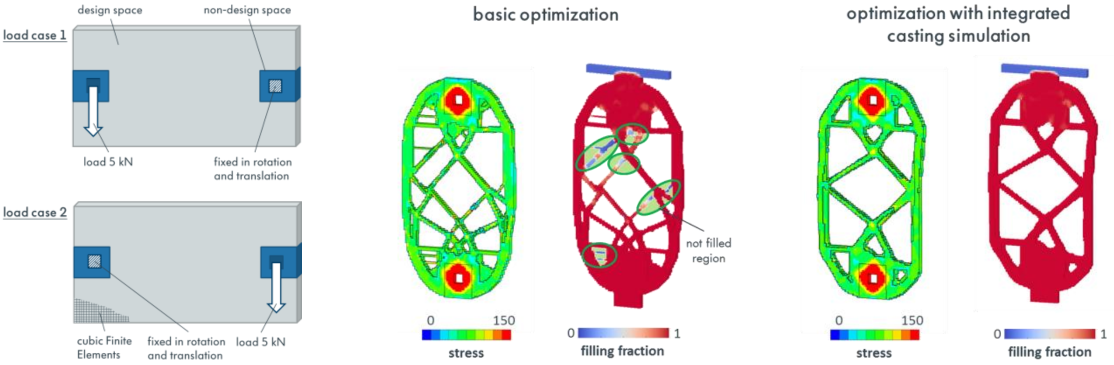


Figure 8: Modelling and result of a basic optimization and one with integrated casting simulation

8. Improved development process

One of the biggest challenges around the topology optimization for the next years is the conversion of the final optimized meshes in CAD geometries. Nowadays, the designers have to create a new part design with a smoothed result structure as design proposal. This step is very time consuming and some features of the optimization result get lost.

To improve this procedure, at least two steps are necessary as a minimum. First the result must be smoothed and secondly the smoothed structure must be described with CAD geometry elements to achieve a CAD design, which fulfills necessary design rules and can be modified.

The current smoothing algorithms do not allow transferring all the geometry information achieved by topology optimization to the CAD program. Surface mesh smoothing is a field studied for decades, however algorithms such as Laplace iterative smoothing, marching cube algorithm and the smoothing algorithm proposed by Wang and Wu still do not solve one of the biggest problems in the mesh smoothing of topology optimization results [32, 33, 34]. This problem is schematically represented in figure 9 on the left side. The left picture illustrates that the part corners are always rounded and the correct information in these specific zones is always lost. Even the new developed smoothing methods that are focused in not shrinking the final volume, don´t allow to solve this problem.

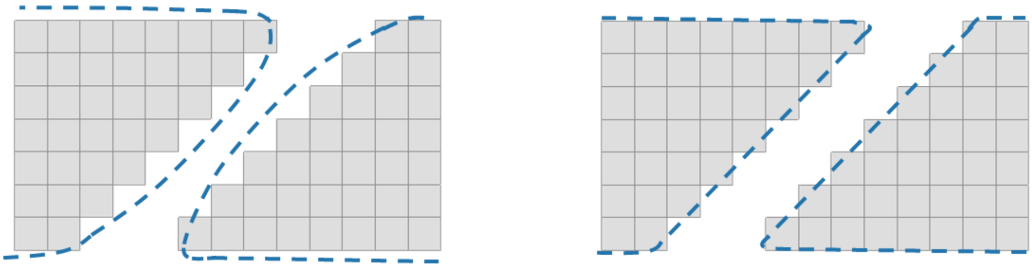


Figure 9: current smoothing result on the left side and needed result on the right side

The needed smoothing algorithms must be able to transfer the shape features, defined in the optimization results, to the final CAD geometry, without the loss of geometrical information. The target design should be changed to the characteristic of a part designed by engineers with clear feature lines. As a possible intermediate step, geometry elements can be written in dead geometry formats like IGES and STEP. The benefits are a strong reduction of the size of the files and resulting handling advantages, the distance between lines can be measured and they can be used for sketches. In the final step, the feature lines and surfaces must be transferred inside the CAD programs.

9. Conclusion

The presented paper describes four future challenges for structural optimization in order to extend the advantages of the topology optimization to fields, where today manual development loops must be accepted. If an optimization algorithm can handle acoustic and crash requirement, it will be possible to use it for more parts and applications, especially if also sheet structures or hybrid parts should be the result. The quality of the first design proposal will increase strongly and due to this, new possibilities of weight and cost reductions are offered. By saving weight, fuel consumption and CO_2-emissions can be additionally reduced. Beside these effects, also development time at the beginning of a project can be saved.

With the integration of the manufacturing process, the resulting part design follows not only mechanical aspects. As first step, the casting parts are the main focus. In each optimization loop, an additional casting simulation will be executed. Due to this, the castability gets a strong increase and weight and material costs stay on the same level in current projects. On the one hand, manual development loops for improving the quality of the casting process can be reduced and on the other hand also in the manufacturing process costs will be saved.

The fourth and last future challenge takes care of the process after the end of the optimization and the next steps of the part design. Today, a lot of design work must be invested to find a first CAD-design of the part. The today used smoothing algorithm changes the surface of the optimization result with possible influences to the mechanical behavior. Unnecessary weight could be added and feature lines get lost. With a new smoothing algorithm these negative effects can be avoided. After finding a way to generate CAD design automatically more development time and costs can be reduced.

With all four future challenges, the development of mechanical components can fulfill in the next years the ambitious targets inside the automotive industry.

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