Integration of topology and sensitive shape optimization into the product development process

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Summary:

The product development process according to VDI 2221 consisting of PLANNING, CONCEPTUAL DESIGN, DESIGNING and ELABORATING is the most convenient way of turning constructive ideas in a feasible design and bringing them to marketability. In the context of increasing traffic pollution and decreasing fossil resources, various government measures, like the EU strategy to reduce CO_2 emissions from cars, were implemented in order to lower emissions and rise up fuel efficiency. These requirements are accompanied with the idea of lightweight design.
During the last few years the finite element analysis (FEA) has been firmly positioned in the product development process. It is possible to reduce design space manually in an iterative way after each numerical calculation until certain critical values, like the maximum tensile stress or maximum deflection, are obtained. To speed up these manual operations, further optimization methods like the topology optimization, generating completely new designs, and the shape optimization, varying the devices' characteristical geometries, were developed.
Despite the necessity to integrate numerical methods for lightweight engineering in the product development process it is hardly state of the art.
Therefore, the phases of the product development process are supplemented by topology optimization, and by shape optimization.
This process chain is used to find the optimal design for a brake pedal of an electric Formula Student race car. Within this process it is possible to reach a final structure that is 77 % lighter, compared to a first draw with a simultaneous low level of deflection and equivalent stresses.
Both the topology optimization and the shape optimization are powerful tools to tweak product designs, especially when they are integral methods in the development process.

Keywords:

Topology optimization, shape optimization, sensitivity analysis, VDI 2221

1 Introduction

The product development process according to VDI 2221 consisting of PLANNING, CONCEPTUAL DESIGN, DESIGNING and ELABORATING is the most convenient way of converting design ideas in a feasible market-ready conceptual design. In the drive of the last decade towards increasing traffic pollution and decreasing fossil resources, various government measures were implemented in order to lower emissions and rise up the fuel efficiency. These requirements are accompanied with the idea of lightweight design. [1][2][3]

During the last few years the finite element analysis (FEA) has been firmly positioned in the product development process. With this tool it is possible to reduce design space in an iterative way manually after each numerical calculation till certain critical values, like the maximum tensile stress or maximum deflection, are obtained. To shorten this manual work, further optimization methods like the topology optimization, generating completely new designs, and the shape optimization, varying the devices' characteristical geometries, were developed. [1][2]

Despite the necessity to integrate numerical methods for lightweight engineering in the product development process it is hardly state of the art. [1]

Here, the phases of the product development process are supplemented by topology optimization, with HYPERWORKS' solver OPTISTRUCT and shape optimization with ANSYS WORKBENCH. This process chain was used to find the optimal design for a brake pedal of an electric Formula Student race car. [1]

2 Theoretical background

Today, physical experimentation has as far as possible been replaced or eliminated by computational simulations. Therefore in this chapter the theoretical background of the computational tools like finite element analysis, topology and shape optimization and their relationship to each other is briefly discussed.

2.1 Finite element analysis

To examine, how a part is deflected under predefined loads and boundary conditions the finite element analysis is a tool state of the art. By assuming a linear elastostatic simulation the Hook's law is the fundamental equation

$$\boldsymbol{K} \cdot \boldsymbol{u} = \boldsymbol{F}$$

with $\boldsymbol{K}$ is the stiffness matrix, $\boldsymbol{u}$ represents the displacement vector and $\boldsymbol{F}$ the force vector. Based on one finite element it is possible to calculate stresses σ from the calculated strain ε and Young´s Modulus E

$$\boldsymbol{\sigma} = E \cdot \boldsymbol{\varepsilon}$$

These two main results, $\boldsymbol{u}$ and $\boldsymbol{\sigma}$**,** determine on the one hand if the simulated model fails or not and on the other hand they are the basis for the topology and shape optimization. [3]

2.2 Topology optimization

The aim of the topology optimization is to create new structures, with a 0-1-distribution of material, under consideration of an objective function. '0' means the element has no material (void) and '1' defines an element as solid element. One example, which is investigated in this paper, is the maximization of the stiffness respectively the minimization of the compliance C:

$$\min C = \boldsymbol{u}^T \boldsymbol{K} \boldsymbol{u}$$

among the constraints

$$\begin{gathered} \boldsymbol{K} \cdot \boldsymbol{u} = \boldsymbol{F} \\ V(x)/V^* - 1 \leq 0 \\ 0 < x \leq 1. \end{gathered}$$

Thereby $V(x)$ represents the target volume and V^* is the material resource constraint. The main variable, which is calculated by the topology optimization algorithm is the design variable x. In topology optimization software there are many different ways to solve the iterative procedure, like the method of moving asymptotes or optimality criteria, which will not be discussed further. [5][6][7]

2.3 Sensitive shape optimization

To reduce stress peaks at different areas of the model the CAD-based shape optimization with design of experiments (DOE) and response surfaces are good means to an end. As a result there can be chosen stresses or weight to vary. First, different areas have to be selected, where the algorithm can modify the surface of the model. These regions are mostly notches or radii, where, based on experience, high stresses can be expected. To reduce the simulation time of one design proposal response surfaces methods are a good instrument. The optimization will be performed on the response surfaces, while fitting the response surfaces on sets of nodes at the design area. [8]
To solve the optimization problem there are many possible algorithms, whereat the sequential linear programming (SLP) and the sequential quadratic programming (SQP) are the most public and well known algorithms. A new approach is the successive response surface method (SRSM), which takes oscillating into account. [5]

3 Integration of topology and sensitive shape optimization into the product development process

Within PLANNING - the detailed clarification of the task - the requirements concerning the brake pedal, are defined. A prior process of planning, including the vehicle's overall development, led to a design-specification-sheet, which includes all requirements and wishes concerning the package space, material as well as boundary conditions. [1][2]
In the next step, the CONCEPTUAL DESIGN determines a basic product solution, which most likely meets the requirements. Based on the design specification sheet and a CAD-package-space-model (CAD-PSM), which was developed in PTC's PROENGINEER 5.0, topology optimization with the program HYPERWORKS 12.0 was used to find a CONCEPTUAL DESIGN. [1][2]
DESIGNING is the development of a design solution. Based on the CONCEPTUAL DESIGN caused by topology optimization, a parametric CAD model is build up, which undergoes a sensitive shape optimization in the process chain's next step. This means that an upstream sensitivity analysis, which is performed in ANSYS WORKBENCH 14.0, filters and optimizes the parameters with the greatest influence on the calculated solution in order to achieve the objectives, set out in the design specification sheet. [1][2]
In the last step, the final design of the braking pedal is being ELABORATED by product-specific documentations like technical drawings, production and assembly specifications and CAM data.
The flow chart in Fig. 1 shows an overview of this virtual product development process. [1][2]

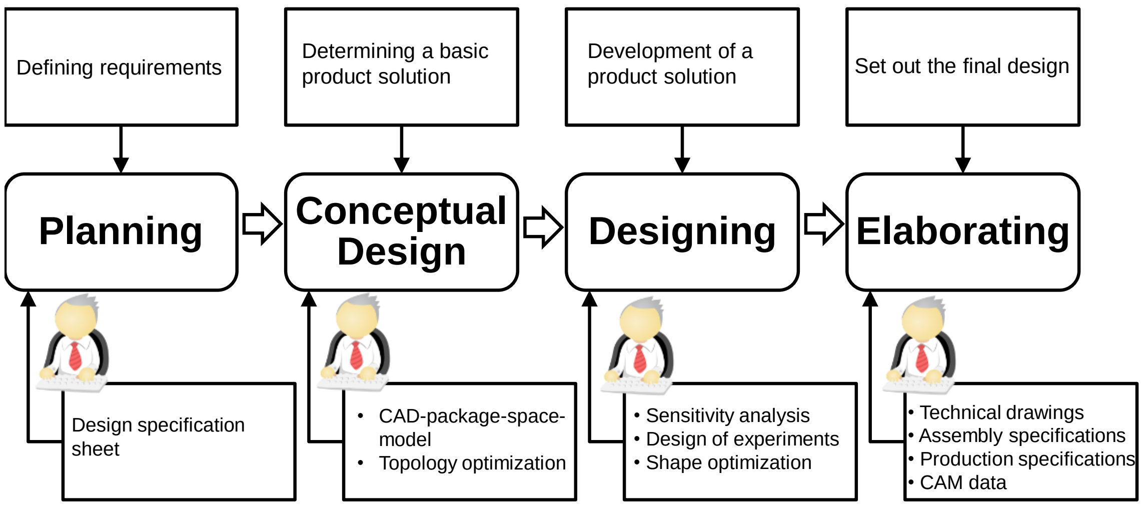

Fig. 1: Overview of the virtual product development process

3.1 Planning

According to the basic rules of the Society of Automotive Engineers (SAE), the brake pedal as part of the braking system has to fulfill specific requirements to be able to participate in competitions of the Formula Student. These necessities state the boundary conditions the brake pedal has to sustain and its material to guarantee safe life behavior. Therefore, they have to be marked as requirements in the specification sheet.
Additionally, in order to achieve the most efficient design for this application, the specification sheet is extended by further entries regarding optimization boundary conditions. An excerpt from this design specification sheet is shown in Table 1.

Table 1: Excerpt from the design specification sheet

General specifications		*Required*
Occurring Force*:*	2000 N	yes
Material:	steel/aluminum	yes
Design specifications		
Minimum weight:		yes
Minimum compliance:		yes

This document provides the basis for a basic product solution and a CAD-PSM, which is the initial point for the next step in process chain.
A detailed Computer Aided Design (CAD) model of the braking system's elaboration is shown in Fig. 2.

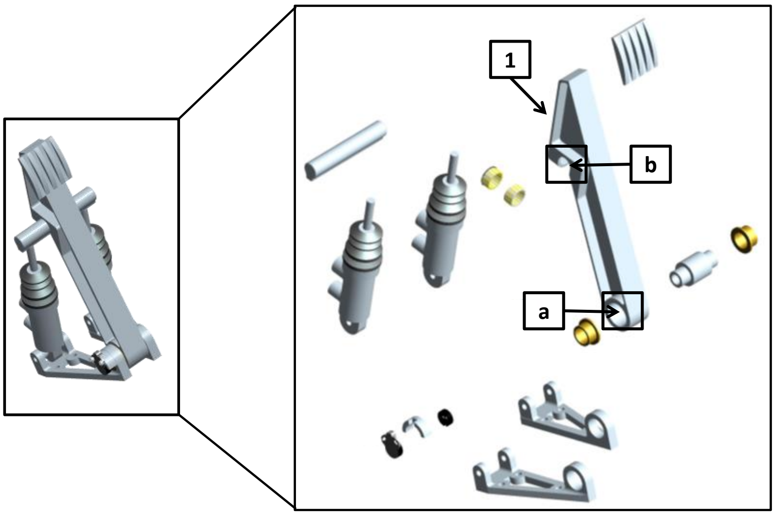

Fig. 2: CAD model of the braking system and exploded view: Braking pedal (1), rotational bearing (a), bearing for the arm of balance (b)

3.2 Conceptual design

In order to achieve a CAD-PSM it is necessary to generate a structure that is as common as possible. This measure is intended to provide the optimization algorithm a preferably general structure and to prevent the formation of certain topologies because of geometric conditions. It is also essential to separate the generalized model into design areas, which need to be changed and non-design areas, which need not be changed. Fig. 3 shows this principle applied to the meshed CAD-PSM. The part was meshed in HYPERWORKS and consists of quadratic tetrahedrons (72,283 Elements, 120,905 nodes). The load (2,000 N) is applied on the front of the braking pedal. Constraints like the rotational bearing and the bearing for the arm of balance are realized with multi point constraints (MPC).

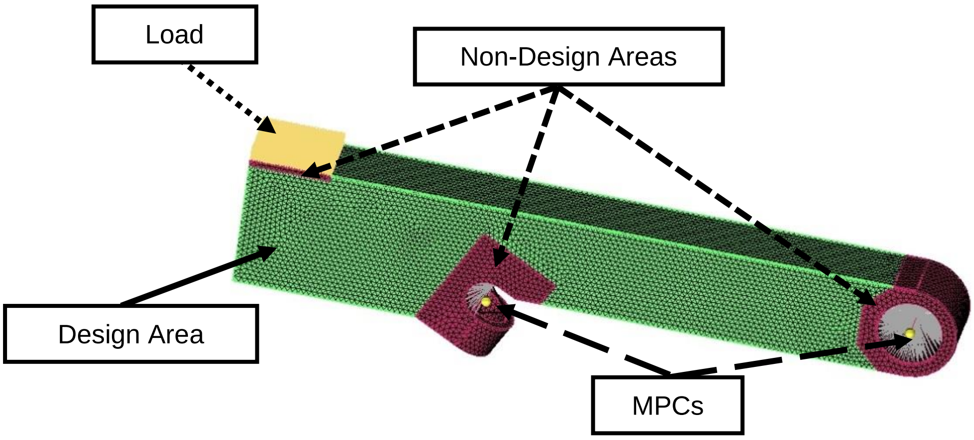

Fig. 3: Meshed CAD-PSM, separated into design and non-design areas, applied load, multi point constraints (MPC)

To find the best combination of the optimization parameters in OPTISTRUCT, simulations with various objective functions and restrictions are performed. Regarded objectives are minimizing the mass (*min(m)*) and minimizing the compliance (*min(C)*). Limited restrictions are a certain value of stress, deflection and mass. A summary over the series of experiments is given in Table 2.

Table 2: Overview of optimizing parameters

Series of experiments		
1. Objective function:	*min(m)*	
Restriction:	σ_{max} < 115 N/mm^{-2}	u_{max} < 0.32 mm
2. Objective function:	*min(C)*	
Restriction:	massfrac < 0.3	mass < 150 g

3.3 Designing

After choosing an optimized version from the prior step, a new CAD model can be build up on this basis in order to generate an explicit geometric contour, which can be further processed. Fig. 4 shows the STL export of one result of the topology optimization and its associated reengineered parametrical CAD part.

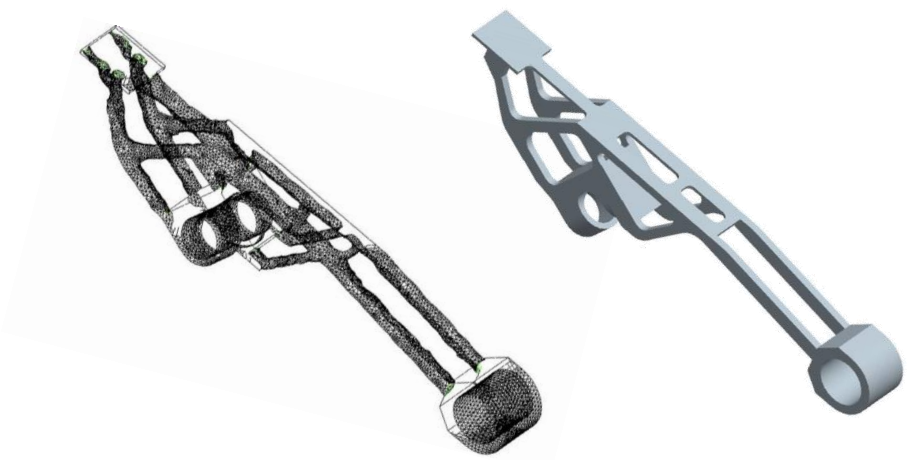

Fig. 4: Left: Exported result of topology optimization; Right: Reengineered braking pedal

Now having a parametrical model, the brake pedals reengineered geometrical parameters are varied target oriented in the sense of a response surface optimization. To minimize occurring stresses and deflections, it is necessary to determine two calculation runs with overall 27 geometrical variables (Fig. 5).

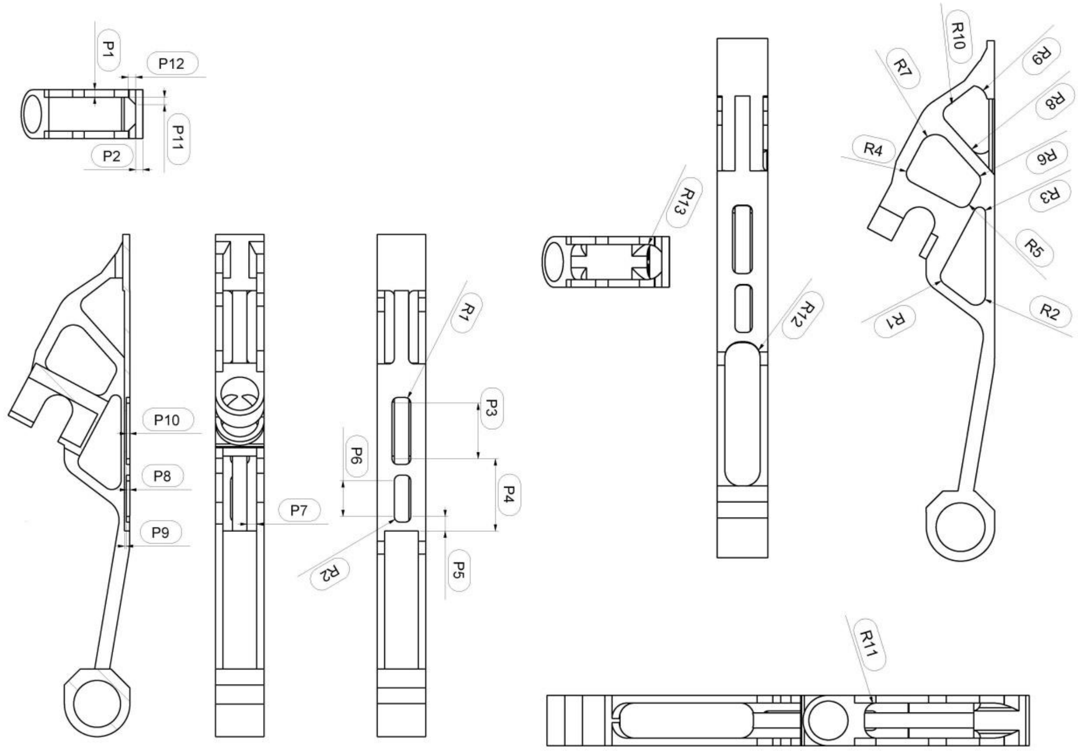

Fig. 5: Left: Parameters for the first run (14 parameters); Right: Parameters for the second run (13 parameters)

In order to reduce the amount of parameters and identify the most influential ones, sensitivity analyses are being performed, in this part of the process chain. In the following optimization, determining the requirements for the target design is necessary and to calculate them, based on a response surface.

3.4 Elaborating

In the last step of the product development process the optimized parameters are adopted in the parametrical CAD model and a final FEA is performed to verify the design. If the results hit the expectations, creating technical drawings or Computer Aided Manufacturing (CAM) data for the manufacturing is possible.

4 Results

The following chapter presents the results of the steps CONCEPTUAL DESIGN and DESIGNING, which include the topology optimization, the sensitivity analysis and the shape optimization, in detail.

4.1 Conceptual design

Developing the CAD-PSM (Version 1) of the braking pedal, based on the design specification sheet, was possible. To ensure that this variant can withstand the occurring forces and to get the stresses and deflections, a FEA is being performed.
Fig. 6 shows the occurring deflections, stresses and characteristical values of the component, which is assigned with aluminum EN AW 7075 as material (Density: 2.8 g/cm^3, E-Modulus: 72,000 N/mm², Poisson’s ratio: 0.3; Tensile strength ~400 N/mm²).

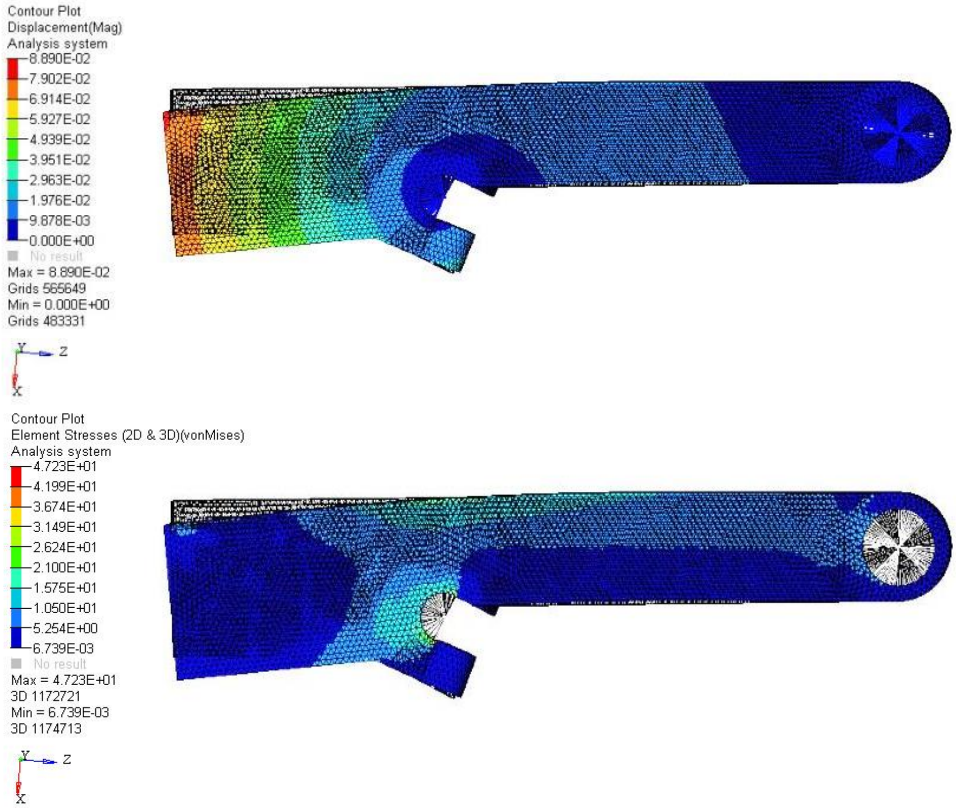

Fig. 6: Top: Plot of the deflection (max.: 0.09 mm); Bottom: Plot of the stresses (47.23 N/mm²); weight of the brake pedal 72.50 g

Based on these results and the defined optimizing parameters in Table 2 the topology optimization can be performed in HYPERWORKS.
The resulting plots show design proposals with the distribution of element densities. Structural important elements have a value close to '1', whereas more unimportant ones tend to '0'. An overview of the optimized structures gives Fig. 7.
Overall four optimization runs are being performed to find the design proposal which seems to be most appropriate for the new structure. According to the design specification sheet and in the sense of lightweight engineering and motorsports the overall mass and the structure's rigidity are the essential factors to make this decision.
In the first two optimization runs, the mass is being set as objective function (*(min(m)*). With respect to the restrictions a stress threshold value ($\sigma_{max} < 115$ N/mm^{-2}) limits 'Topo 1' and a maximum deflection ($u_{max} < 0.32$ mm) 'Topo 2'.
In the third and fourth optimization run the compliance is being minimized (*(min(C)*) to get a structure of maximum rigidity. To simultaneously lower the overall mass, the version 'Topo 3' is being restricted by a fraction of the initial design mass (massfrac < 0.3), whereas in 'Topo 4' the mass is directly being restricted (mass < 150 g).

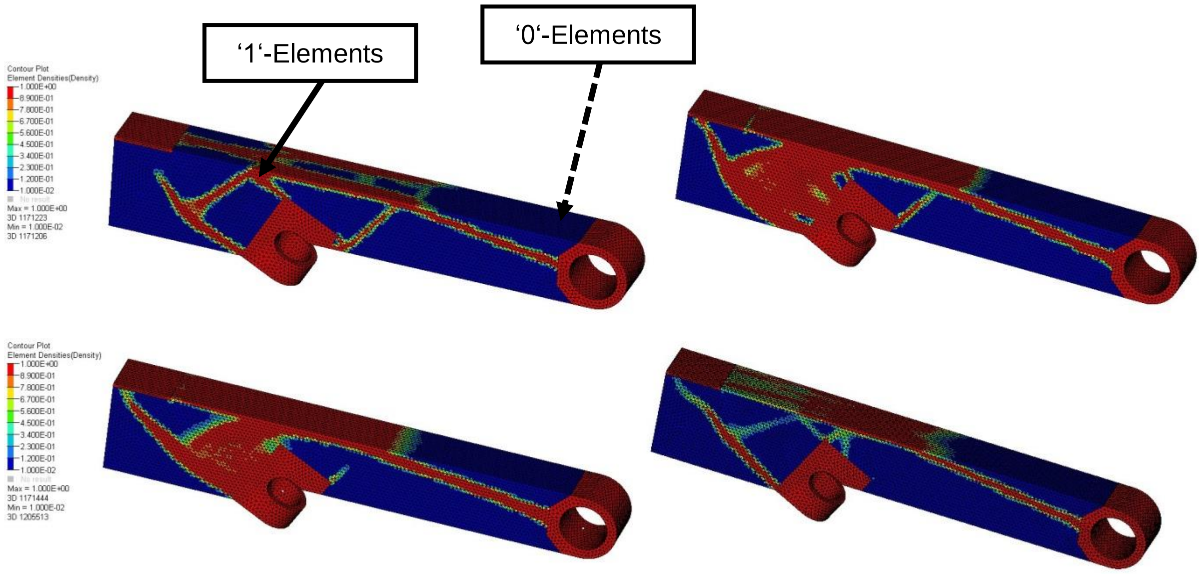

Fig. 7: Plot of element densities; Top, left: ‘Topo 1’, *min(m)*, σ_{max} < 115 N/mm^{-2}; Top, right: ‘Topo 2’, *min(m)*, u_{max} < 0.32 mm; Bottom, left: ‘Topo 3’, *min(C),* massfrac < 0.3; Bottom, right: ‘Topo 4’, *min(C),* mass < 150 g

Having applied a fix lower threshold value for each version’s element density, only the elements above remain in the structure. Further on, finite element analyses need to be checked to get information about the occurring deflection, stresses and mass.

Fig. 8 gives an overview of the percentage change of these component’s properties compared to the breaking pedal Version 1.

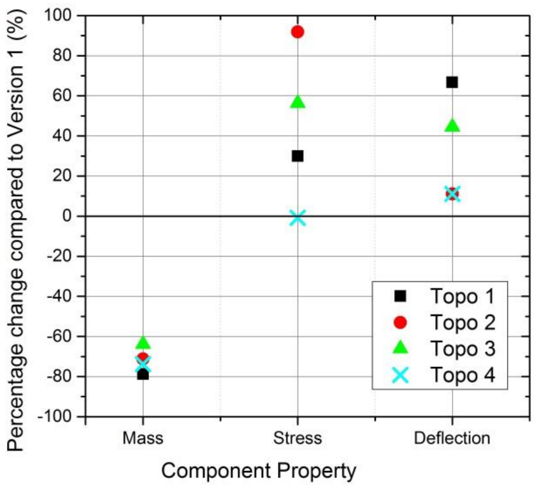

Fig. 8: Percentage change compared to mass, stress and deflection of Version 1

According to the diagram, a selection process has to be carried out. As a result the variant ‘Topo 1’ is most appropriate. In comparison to the other versions, it has the biggest potential to minimize the mass. With an estimated value of 78 % it will result in a structure of 154 g. Because of the lighter and thinned out structure, higher stress and deflection values have to be expected. In these categories ‘Topo 1’ has to be expected to have 25 % higher values of stresses, which means 61.35 N/mm^2, and 66 % greater values in deflection, what results in 0.15 mm. Overall and according to the design specification sheet, this structure provides the best optimization potential and is being further on perused as design basis for the next step in the product development process.

4.2 Designing

Based on the braking pedal’s reengineered structure and the determined geometrical variables (compare Fig. 4 and Fig. 5) two sensitivity analyses were performed in ANSYS WORKBENCH to screen the most influential ones on the overall deflection, mass and stresses. Fig. 9 shows the results of the two calculation runs.

In the first run three parameters (P1, P9, P11) can be identified having a great influence on the maximum deflection and mass. As an example changing parameter P1, the braking pedal's wall thickness has the biggest influence decreasing the maximum deflection but also increasing the braking pedal's overall mass.
In the second run, there could be identified four radii (R4, R5, R7, R8) with great influence on deflection and stresses. For example, R8 has an immense influence on reducing occurring stresses, but has the least effect of the four radii to reduce occurring deflections.

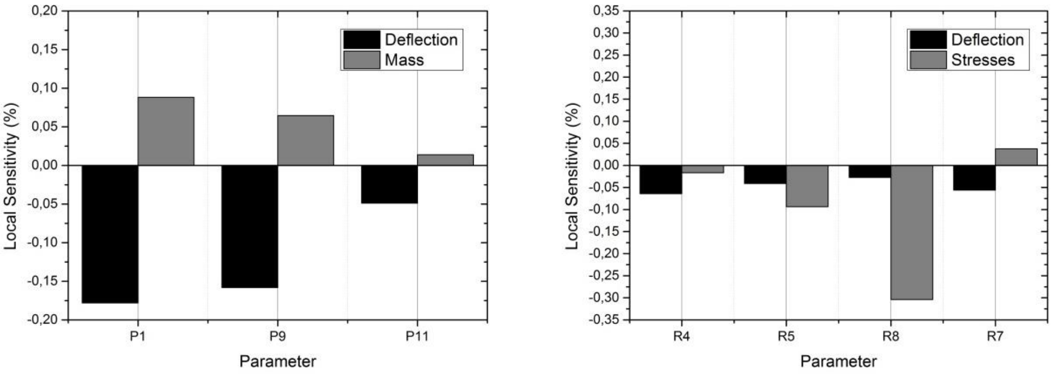

Fig. 10: Sensitivity analysis; Left: First run; Right: Second run

Having the knowledge which parameters mostly affect the occurring deflection, stresses and mass, the braking pedal can be shape optimized.
In the ensuing optimization the requirements related to the objective design are formulated and calculated based on the response surface. Overall two optimization runs were necessary to reach the final design. Restricting the mass (m < 180 g) in the first optimization run and setting the deflection (min(u)) as objective function, all designs fulfilling the target are shown in a Tradeoff-plot in Fig. 11. As a result, decreasing the mass from 180 g to 170 g, without strongly raising the maximum deflection (from 0.20 mm to 0.23 mm) is possible. Having chosen the best design proposal, the parameters calculated by the response surface are adopted to the parametrical model of the braking pedal and a new finite element analysis has to be carried out.
In the second optimization run the maximum equivalent stress is being restricted (σ < 150 N/mm²) and the deflection is set as the objective function (min(u)). The Tradeoff-plot for the second run in Fig. 11 shows the possibility of minimizing the stresses to 128 N/mm² with a parallel minimization of maximum deflection to 0.21 mm.

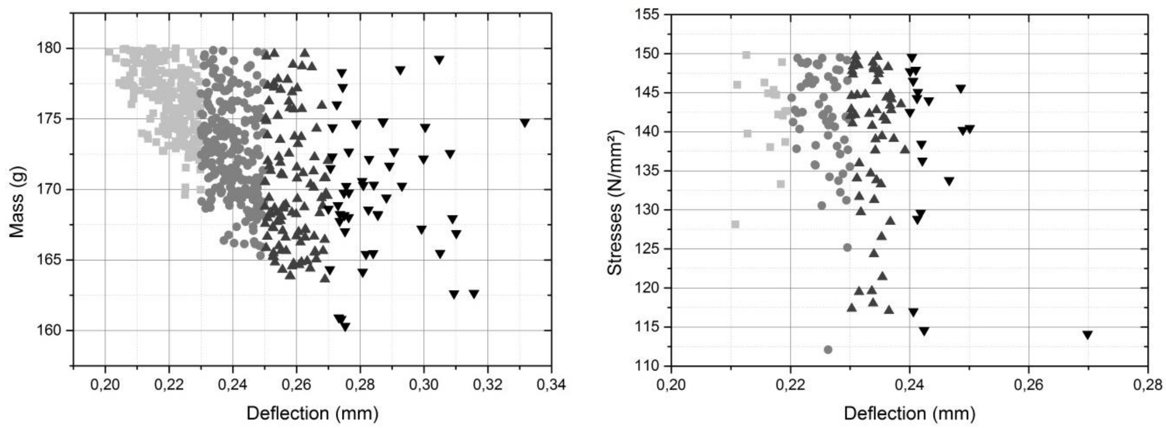

Fig. 11: Left: Tradeoff-Plot for calculation run 1; Right: Tradeoff-Plot for calculation run 2; good designs (light gray, rectangle), bad designs (black, triangle)

Adapting the calculated parameters from the second optimization run, a final finite element analysis has to be performed to obtain the final stress, deflection and mass values. Fig. 12 shows the final version of the braking pedal with a maximum deflection of 0.2079 mm, stresses of 127.66 N/mm² and a mass of 164 g.

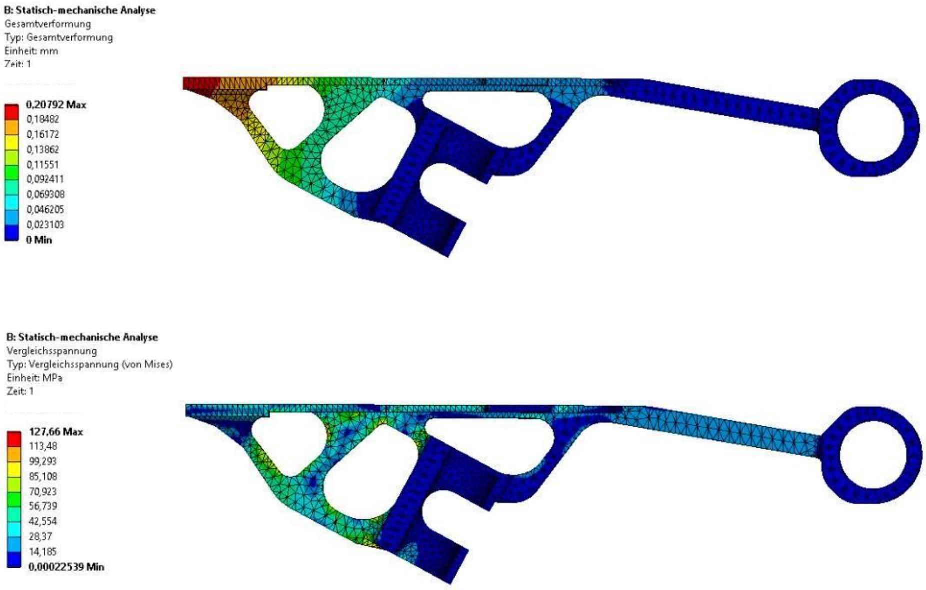

Fig. 12: Final version of the braking pedal; Top: Maximum deflection 0.2079 mm; Bottom: Maximum equivalent stress 127.66 N/mm²

5 Summary and outlook

In order to find the best design for a breaking pedal, the topology optimization and sensitive shape optimization were integral components of the product development process.

Setting design goals straight from the beginning in a design specification sheet and using numerical methods like the topology optimization during the conceptual design phase, and the sensitive shape optimization in the designing phase, it was possible to shorten the product development process and to lower the weight of the braking pedal's first version by approximately 77 % from 723.5 g to 164 g with simultaneous low maximum deflection (0.2079 mm) and equivalent stresses (127.66 N/mm²).

With regard to the EU strategy to reduce CO_2 emissions from cars, this procedure is an effective way to achieve these objectives. Regarding to the breaking pedal's weight reduction, the specific CO_2 emission averaged over all newly registered cars of a given fuel type could reduce the CO_2 emissions from 130 gCO_2/km to 129.97 gCO_2/km.

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