RESOURCE-EFFICIENT CFRP DESIGN METHODOLOGY FOR AUTOMOTIVE SYSTEMS

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ABSTRACT

The high potential of superior materials like CFRP-composites to save weight within automotive systems, has been shown several times over the past decades. The current trend however, to use a modular design approach and numerous carry-over parts delivers a cost efficient design but makes it highly challenging to implement new materials like composites into an existing product architecture, without running into a Black Metal-Design. A resource-efficient purpose design implements the composite parts where the function and location justify the higher costs and uses cost efficient materials where the weight saving potential is low. In order to support the development process of a resource-efficient multi-material system and to solve this area of conflict a new methodology is developed and presented in this paper. The approach is aligned to the standard VDI2206 [1] with the combination of a topology optimization and the material selection process by Ashby. Under consideration of the different loads and restrictions a topology optimization of the system is executed and the result is divided into different subsystems. These subsystems are then analysed regarding their major load case (bending, torsion, compression, etc.) and by using the Ashby-approach a comparison of costs and weights is conducted. With the definition of a cost/weight ratio, a decision regarding the best suited material is made. With these results, existing systems with familiar loads can be analysed regarding their lightweight potential and the possibility to implement composites like CFRP. The methodology itself supports the process and helps the design engineer to analyse the system and structure the work.

Within this paper the methodology is applied and validated using the example of a frameless door system. Exemplary one substructure, with the highest potential for the implementation of CFRP is discussed in greater detail (weight saving 63.3 % with additional costs of 10 €/kg saved).

1 INTRODUCTION

"The right material at the right place for the optimal function!" (Köhler, 2012). When it comes to lightweight design within the automotive industry everybody seems to agree to this quote from Head of lightweight design at Audi, Dr. Olaf Köhler. The motivation for lightweight design within the automotive industry is obvious due to the legal legislation to reduce the CO_2 output of vehicles by 2020 to 95 g per km in addition to the positive impact onto the dynamic of a car. The way to achieve this goal often leads to superior materials like Carbon Fibre Reinforced Polymers (CFRP). The biggest challenge in order to design a comprehensive lightweight CFRP system is to reduce the high material and manufacturing costs. The development over the last years led to the highly promoted multi material design, which includes the right material at the right place for the optimal function. This leads to a resource efficient design, where the trade-off between cost and weight saving justifies the implementation of composites like CFRP. Thus high tech materials such as CFRP are applied at spots where the technical advantages are significant and conventional materials are kept if no or little advantage is achieved.

The question is how to validate where CFRP is most beneficial and where other materials are more cost efficient regarding their required performance and hence more likely to be implemented. The material selection process by Ashby [2] illustrates one opportunity to answers this question and find best suitable material substitutions, by combining a tremendous material database with a

comprehensive mechanical engineering understanding. Figure 1 shows the four major steps of this approach. The first step is to translate the current design into material dependent functions and properties (translation). The complex geometry has to be simplified in order to derive functions that include all constraints and highlight the free variables. Usually the crucial part is to identify the main load case and the load bearing geometry. All material dependent variables form the material index. The constraints of the design (e.g. maximum service temperature, minimum fracture toughness, etc.) are then used to eliminate some first material options within the second phase (screening), which can be visualized in a material diagram or "Ashby-chart" (figure 1, upper right picture). With the help of the material indices the "Ashby-charts" are then used to optimize the choice of materials. All materials that have the same performance are on the same (red) line (figure 1, lower left picture) and by moving these lines further away from the origin the performance increases (ranking). The final step (information) is seeking supporting data within the environment of the part or the list of requirements to identify the best suited material for this specific application (for detailed information see [2]). The approach is very helpful, since it puts economic, physical and even ecological data into a clear relation which allows the engineer to objectively take a decision for the material selection. The selection is based on quantified data, thus can be easier justified and reproduced.

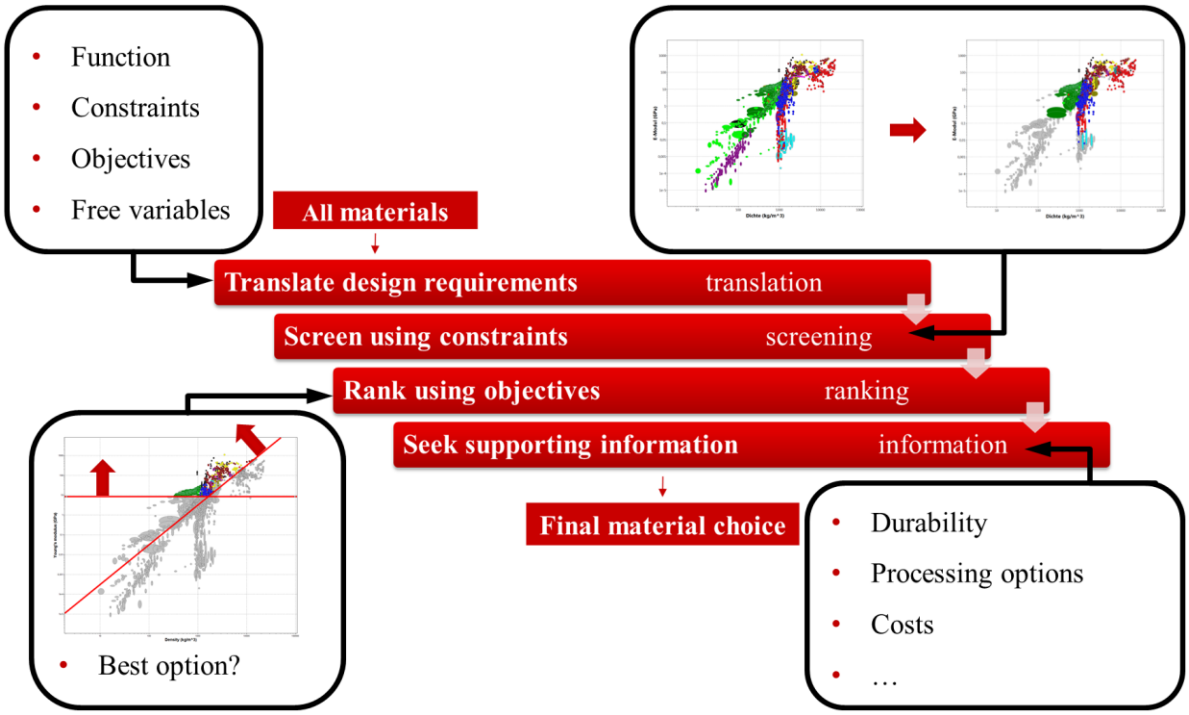

Figure 1: Material selection process by Ashby

The past has shown that especially for the implementation of CFRP into a vehicle, structural components promise the highest potential to justify the higher material costs by delivering the highest weight saving. That is where composite parts utilize their anisotropic material properties best, by bearing the loads with the fibres, ideally along the load path of the system. Hence, finding these load paths has to be the first step in order to enable the full potential of CFRP parts. In current assemblies within a car, most load paths are already determined due to the product architecture (the link between functions and their implementation into parts) and defined carry-over parts [3] that form the basis for platform strategies. The current trend of the OEM is to use platform strategies to reduce the development costs of the vehicles, since several products can share the same platform [4]. The importance of the correlation between product architecture and material selection process is significant [5]. Often these pre-defined product architectures make it difficult or even impossible to introduce new materials, especially composites into a system. Pre-defined load paths and the underlying load cases may imply a multiaxial stress for the part, which makes it difficult to align the fibres to the load case or vice versa. Nevertheless a system lightweight approach that considers every part within a product

and its influences onto each other promises the highest weight saving potential [6-10]. Hence the necessity to start a development by scratch is there – however often difficult, expensive or infeasible due to delivery pressure. Nevertheless, for a comprehensive, resource-efficient, fibre feasible lightweight composite design it is inevitable to give the design engineer as much freedom as possible. Translated onto a car system under consideration of the material selection process by Ashby and the requirement to put the material, where it is most beneficial for the whole system, the engineer has to find and define the areas within the available design space, where CFRP parts should be implemented.

In order to do so, a topology optimization has proven to be a very efficient and objective way to fulfil these requirements [11]. The biggest advantage of combining a topology optimization and the material selection process by Ashby, is that the results of the topology optimization can be used directly for the translation phase by Ashby. This leads to a pragmatic way to derive the load cases and identify the main load case, which is the basis of the translation phase of Ashby. A topology optimization can use several algorithms and different methods to develop altered macrostructures, depending on the load cases, the constraints and the objective function. Within this paper the Solid Isotropic Material with Penalisation (SIMP)-method is applied, using the software Optistruct (HyperWorks 14) from Altair. Although the SIMP-method uses isotropic material as an initial point, it is the most common algorithm and usually available within the design departments of the OEM or first tier supplier. Basis of the realized optimization is the reduction of the mass with a target value of 10 or 20 % rest mass under common stiffness constraints (in the automotive industry). As a case study within this paper the chosen engineering system is a frameless automotive door system that gives the opportunity to examine an independent system with high requirements regarding stiffness and lightweight design. In order to model the design space for the topology optimization several elements can be used. The best results (with the same numerical effort) of a topology optimization are generated by using hexaeder elements [12]. Although an automesh-option is not available for these elements, which makes the meshing process very time consuming, they are used within this research. In order to combine all above mentioned topics in an easily accessible way, a methodology is developed that supports the engineer during the design process. Especially to visualize the system approach a methodology is required that allows to understand and evaluate the influence of different materials for different parts on the product architecture. All this leads to the development of the methodology presented in this paper, using the design approach for mechatronic systems as a basis [1]. Although an automotive door system is only partially a mechatronic system it is recommended to use this approach even for fully mechanical system. The big advantage is that the two level "system level" and "component-level" can be considered individually, which helps to understand the influence they have on each other.

2 METHOD

Initial point of every design process is defining the requirements and the available design space [3,13]. As can be seen in Figure 2 the new process starts on the system level with the requirements and the design space for the topology optimization. Regarding the requirements the most important step is to define the trade-off between costs and weight saving. Usually these figures are available for a new part, but depend on the area within in the car, where the weight can be saved. As a basic principle it is said that the higher the part is within the vehicle, the more less weight positively influences the dynamics of the car and the more the costumer is willing to pay. Applied to a door system and the implementation of CFRP as a weight saving material, this leads to the highest potential in the waistrail-area.

The definition of an explicit lightweight-cost ratio in reality is often overlaid by additional soft criteria. Standard requirements, like a safe design are usually "must-be"-requirements of the costumer. These requirements are not explicitly expressed and obvious [14]. The "desired" requirements are specific, measurable and usually technical. Additionally to that, there are the "delighters". These requirements are not expressed since the customer does not know that he wants these functions in the product and hence it is impossible to put some costs against these requirements. These delighters often make it difficult to define an explicit lightweight-cost ratio. The introduction of a composite material for example, might offer the additional opportunity to enlighten the door trim by implementing some

glass fibres within the top ply but it is unclear how much the costumer is willing to pay for that. Since a real design process is overlaid by many potential delighters, it is important to conduct a comprehensive functional analysis [15] to identify potential functions that can be integrated in dependency onto the chosen material.

These requirements and the available design space build the initial point within the process shown in Figure 2. Under the given loads a model is generated and an initial Finite Elements Analysis (FEA) and topology optimization is conducted. The results have to be divided into different sub-elements/components. Since the optimized parts usually have a branching structure, it is useful to separate every branch for the analysis. These sub-elements usually have similar or homogenous load types, which allows the analysis regarding their loads and the resulting stress condition

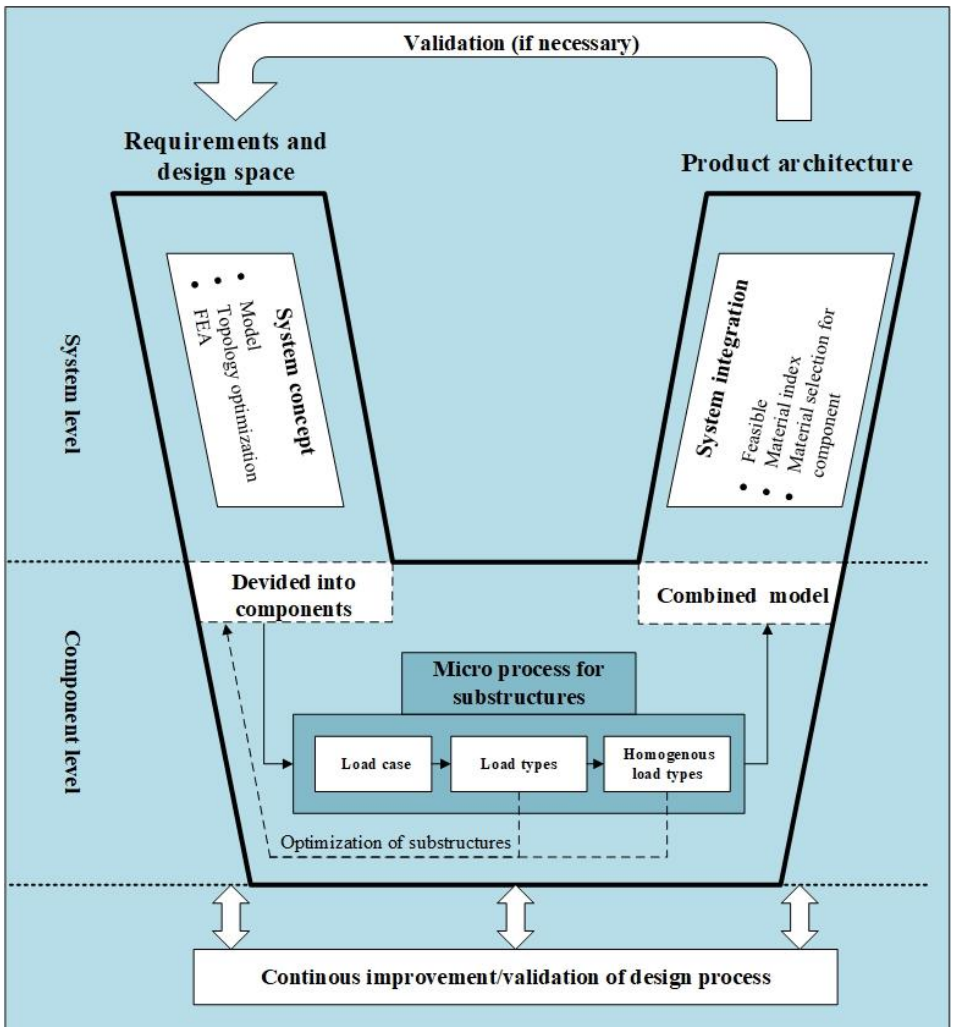

Figure 2: Developed Design process aligned to the VDI2206 [1]

This process is summarized in the micro process (lower area in Figure 2). The results of the topology optimization are exported and re-analysed regarding their load type using an FEA. It is important to understand the main load type in order to combine different branches with the same load type.

A solution to derive the main load type from an FEA is explained in Figure 3. Two trivial FEA are conducted for the load cases bending and torsion on a generic solid beam. By using the “signed von Mises” stress it is possible to identify tensile (red area in Figure 3) and compressive (blue area in Figure 3) stress.

Applied to more complex geometries and load cases the analysis is more challenging and requires some experience but with this information it is possible to develop a first rough product architecture

based on the different load types. In order to develop a resource-efficient product architecture it is important to change the material, where load type or geometry make it beneficial. Hence, the different branches have to be analysed regarding their load type and the same load types are combined to one component. If one load case can be identified as a main load case the Ashby approach can be used to select the best material for this load type.

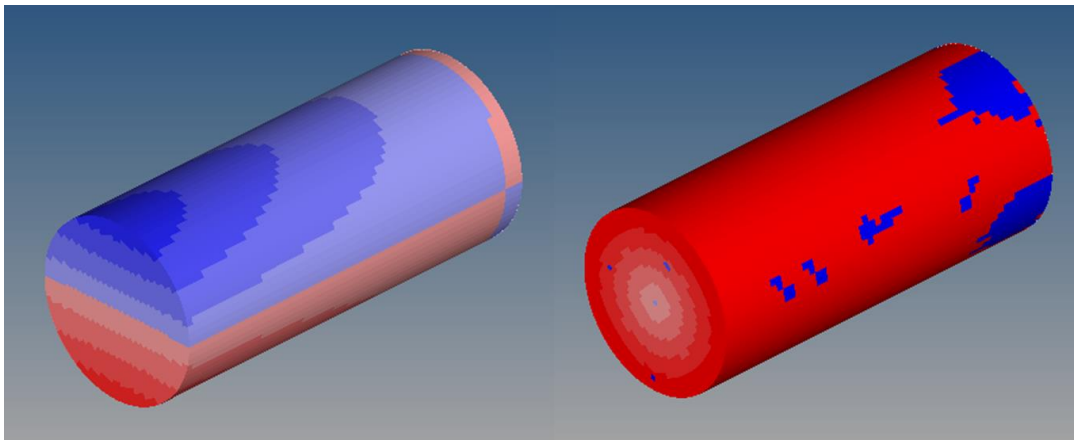

Figure 3: Load case bending (left picture) and torsion (right picture) with hexaeder elements

Considering the implementation of CFRP, the following boundary conditions have to be fulfilled to deliver the best results:

- One main load case (ideally tensile stress), at least three times higher than other load cases
- Simple and drapable geometries (shells)
- Laminar force applications
- Preferable far distance from the centre of gravity of the vehicle (contrary to the gravity acceleration)

A comparison of the different materials and the resulting weights and costs can be implemented into the software CES Selector from GRANTA©. It allows a fast and pragmatic way to estimate the potential weight saving and the impact regarding mechanical behaviour and costs. With a rough lightweight-cost ratio it is possible to set-up a product architecture based on quantifiable figures. For areas, where the load case, the shape, the cross section or the framework do not gain a sufficient benefit, this approach already provides an alternative material that is best suited under the given constraints. Depending on the available time and necessary detailing, a second iteration within the design process, including a topology optimization based on the new materials can be executed.

3 CASE STUDY AND RESULTS

The application of the developed design process can be seen in Figure 4. In order to validate the element size the model is meshed three times with different element sizes (5, 10 and 20 mm). Since an element size of 5 mm lead to an extraordinary high computing time and a sufficient convergence is already seen with an element size of 10 mm the decision to use 10 mm elements is made. In order to guarantee reliable results the model is analysed six times with two different materials and different objective functions (minimum mass and minimum compliance with 10 % and 20 % rest mass). The load cases are divided into the different abuse cases and operation conditions, resulting in 32 different subcases. The standard boundary condition (BC) is a fully closed door mounted on two hinges and the door lock. Two exceptions are defined for the door abuse loads "sag", where the door is only mounted on the two hinges and for the abuse load "over opening", where an additional edge guide is defined, where loads are transferred.

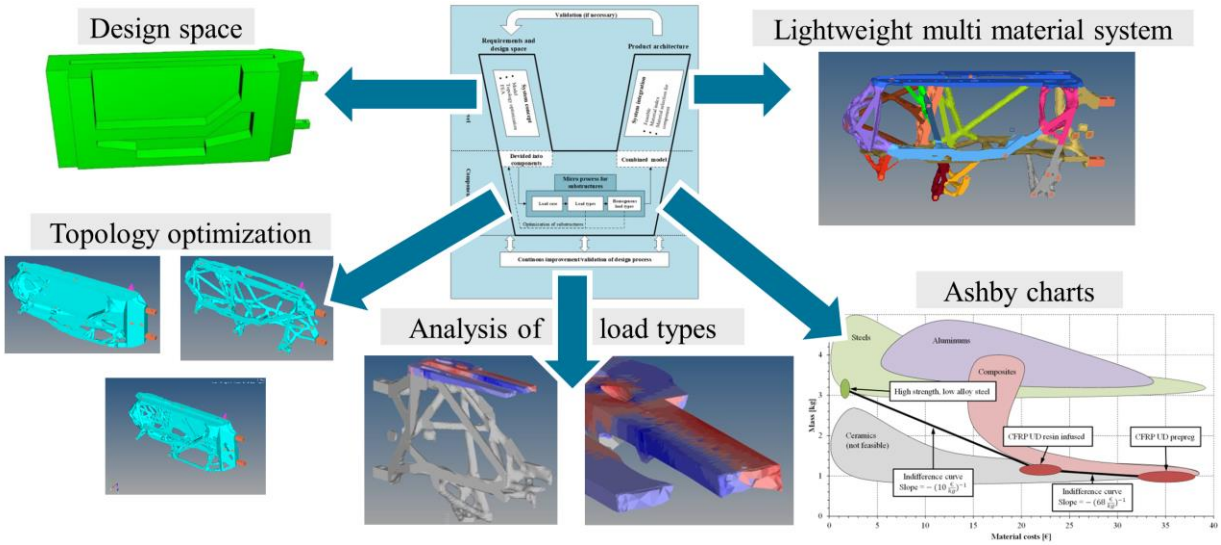

Figure 4: Application of developed design methodology

The best results are generated with the material steel and the objective function “minimum mass”. This model is chosen for further investigation. The optimized structure is divided into the different branches and then analysed in greater detail. For every branch the 32 different load cases are investigated and analysed regarding their load type. For further visualization the optimized structure of the waistrail area (see Figure 5) is shown in greater detail.

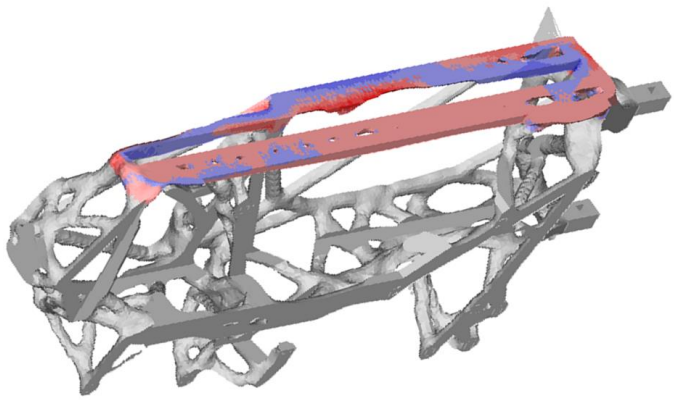

Figure 5: Investigated substructre in the waistrail area

This structure contributes a significant amount to the stiffness of the whole system. It also fulfils the pre-defined requirements for the implementation for CFRP, mentioned above. Except of the two load cases “letterbox inner waistrail” and “letterbox outer waistrail” (pulling the window slot apart), no forces are directly applied during the lifecycle of a door. Hence, the resulting stress is almost exclusively induced by other loads and hereafter laminar loads. Due to its position at the edge of the design space, the optimized structure is a fairly plane geometry and accordingly easy to drape. It is also the substructure that is furthest away from the centre of gravity of the vehicle, which makes it highly interesting for a lightweight design. The most important requirement however, is that one main load case can be defined, that is at least three times higher than the others. To investigate this requirement the optimized structure of the door has to be transferred into a new model with homogenous density. With this model a new FEA can be conducted and the induced stress for every load case is analysed and in dependency of the “Signed von Mises” stress the load type is derived. For this structure the load case “static mirror torque” induced the highest stress. Hence, it is used as basis to normalize the measured stress figures, which can be seen in

Table 1.

Load Case	Load type	Normalized tensile stress	Normalized compression stress
1: Window regulator	Bending around z-axis and torsion around y-axis	0.718 %	0.319 %
2: Static mirror torque	Bending around z-axis	100 %	100 %
3: Over opening door	Bending around z-axis	3.74 %	1.62 %
4: Panel dent stiffness	Bending around z-axis and torsion around y-axis	0.667 %	1.84 %
•	•	•	•
•	•	•	•
•	•	•	•
28: Armrest abuse	bending around z-axis	25.5 %	30.6 %
32: Speaker mountings	bending around y-axis	1.24 %	1.0 %

Table 1: Analyzed load cases with normalized stress

The investigation shows that the only other load case that induces a relevant stress into the structure is the "armrest abuse" load. The normalized stress however is between 25% and 30% and hence less than on third of the load case "static mirror torque". Accordingly the requirement to identify one main load case within a structure is fulfilled. With the results of

Table 1 it is now possible to use the load type and the specific geometry to conduct the material selection process by Ashby. By using the simplified load case of a beam in bending a first analysis for possible materials is conducted. Under the constraints of minimum fracture toughness and the producibility of the specific geometry, the two material families composites and metals are most promising. In order to generate valid and reliable figures, two different cross sections (U-shape and hollow rectangular) for both material families are analysed and in consideration of the real geometry specification, summarized in the Ashby chart in Figure 6.

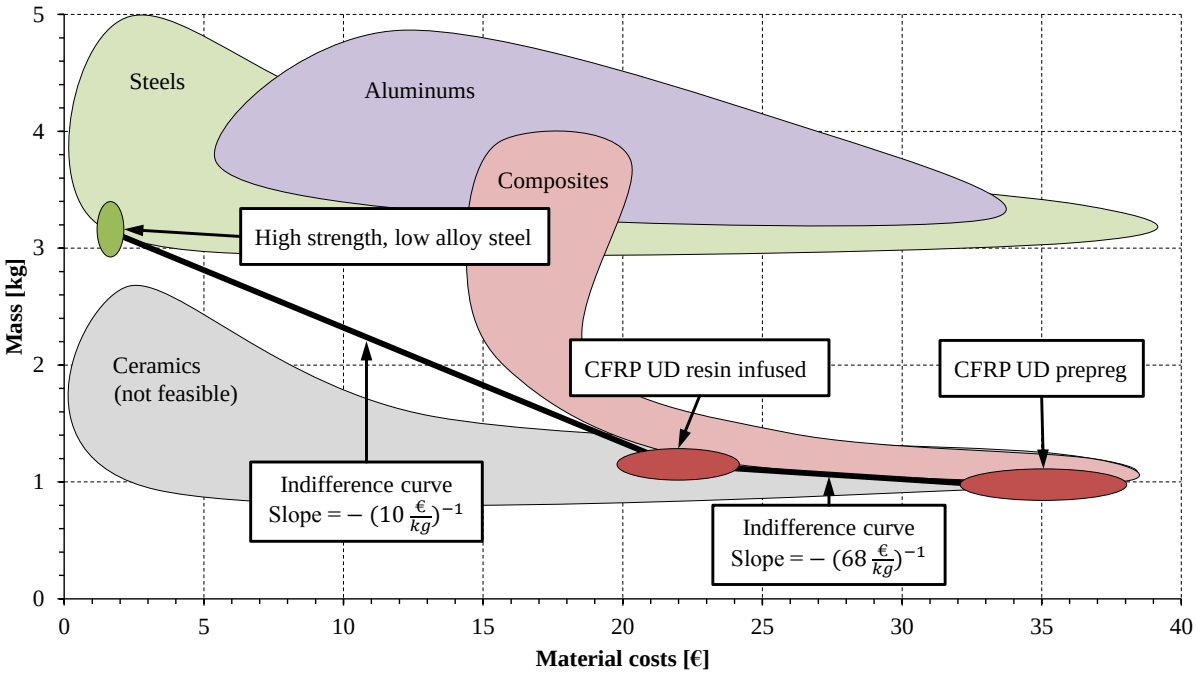

Figure 6: Comparison of different materials with mass and cost for the investigated substructure

It is obvious that CFRP delivers the lightest structure, but also the most expensive one. Surprisingly Aluminium is always more expensive and heavier than steel and hence fully dominated by a steel solution for this use case. The slopes of the indifference curves shown in Figure 6 define the best solution for different frame conditions. If the costumer is willing to pay more than 10 € per kilo saved, he will chose the CFRP resin infused (1.1 kg and 20 €) solution. If he is willing to pay more than 64 € per kilo saved, he will chose the prepreg (1 kg and 30 €) alternative. Otherwise the steel design for 2 € and 3.1 kg is the best solution. The costs in this case are pure material costs, excluding manufacturing or assembly.

With this approach, by using a topology optimization linked to the material selection process by Ashby, it is possible to make first reliable estimations of possible weight savings and estimated material costs, without going into too much detail. Once a decision regarding the preferred materials for the different substructures is made, the results are analysed regarding their compatibleness. Depending on the load cases of the different structures, their assembly strategy and possible geometries, a feasible joining technique is developed. If a combination is not feasible the next best material is reviewed regarding the compatibility on the system level. To support this process a compatibility matrix is used, which allows the examination and fast selection of the best combination of materials.

In the end, a costumer specific product architecture is generated with resource efficient composite parts where the present load conditions and the framework suggest their implementation.

4 DISCUSSION

The applied simplifications within this research lead to future optimization potential. The used cross sections of the sub-elements are not shape-optimized. Many programmes offer possibilities to improve the shape of a part with known forces, even under manufacturing restrictions. Using a shape optimization for every cross section will improve the results, but will not change the overall results.

Once the material is set a second topology optimization considering the different material properties can be a next step to significantly improve the design and enhance the weight saving opportunity. The opportunity of implementing additional “deligthers” and functions can be a third way to justify the introduction of new materials as e.g. CFRP. Aesthetic functions, like the visual integration of CFRP inside the car, can result in an integral shell design. A non-design area with pre-defined material properties in these areas should then be considered for the topology optimization.

A critical view should however be taken with regard to the basis of this research. As mentioned before, current development rarely starts from scratch and existing products and parts are usually implemented in order to reduce the development costs. To start from scratch or at least with the highest possible degree of freedom for the topology optimization in order to gain a sufficient lightweight design and develop a new product architecture, is however the foundation of this research. Future research will focus on the implementation of working surfaces due to carry-over parts.

Another next step will be the implementation of a second topology optimization under consideration of the different materials and eventually a shape optimization for the different subsystems. This will result in a second loop within the methodology. An optimization on the micro level of the material for detailed fibre orientation like a Computer Aided Internal Optimization (CAIO) can be implemented in a third loop within the existing methodology.

5 CONCLUSION

The developed methodology showed how the combination of a multi-material lightweight design and a topology optimised design can be integrated in one design approach under consideration of the system lightweight design. The actual implemented tools were the material selection process by Ashby and the topology optimization with Altair HyperWorks 14. For the detailed impact, this process had on the product architecture, it is referred to [15] and the use of the “METUS-Raute”, which allows to put different functions and their cost in relation. It was shown, how important it is to validate and make objective decisions whether cost intensive composites like CFRP are worth to be implemented, regarding a resource-efficient design.

In a first step the available design space, the justifiable cost per kilo weight saved and the additional requirements were recorded. With this information several topology optimizations with different material properties and objective functions were conducted and the best results were divided into the different branches generating different sub-structures. These were analysed in an FEA regarding their load type (e.g. bending, torsion, etc.) and similar load types were combined to one component. If the induced stress of one load case was at least three times higher than the others, it was identified as the main load case and hence the resulting load type was used as the main design criterion. Using this design criterion allowed the application of the material selection process by Ashby. Translating the load type and existing geometry constraints into an "Ashby-chart" made an objective comparison of different materials and the resulting weight and costs possible. With these charts an objective decision, where the application of composites like CFRP or GFRP is beneficial was conducted. In areas where load type and available design space did not recommend the introduction of cost intensive materials, standard materials were used, leading to a resource-efficient multi-material system.

The used tools, the implementation of the design process in a methodology and the consideration of the realistic framework within the automotive industry allow a practical implementation in an industry environment for the development of new resource-efficient lightweight systems.

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