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Methodical Design Process for structural FRP systems

Jonathan Schmidt[*], Benedikt Heuer[*], Anna-Lena Beger[*], Zhuzhell Montano[*], Hendrik Hoffmann[*], Joerg Feldhusen[*], Dave Cadwell[†]

[*]Chair and Institute for Engineering Design, RWTH Aachen University,
Steinbachstr. 54 B, 52074 Aachen, Germany
j.schmidt@ikt.rwth-aachen.de

[†]BENTLEY MOTORS LIMITED,
Crewe, Cheshire, CW1 3PL, England
dave.cadwell@bentley.co.uk

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Summary: *The fully integrative composite part is the dream of every designer delivering a cost-efficient lightweight design, but due to multiple reasons this is seldom achieved. In order to completely exploit the potential of fiber-reinforced plastic (FRP) parts an adaption of the product architecture needs to be made which involves several risks. Hence a "not-CAD-driven" design process has to be applied to allow quick concept changes on a high level. Using a function based method related to the approach within the standard VDI 2221 [1], a channel and contact model developed by Matthiesen [2] is refined to suit a structural FRP assembly. Furthermore, elements of Ashby [3] and Hufenbach [4] are applied and a morphological matrix is used to develop different product architectures and concepts. The key results of this paper are the detailed methodology and its implementation at Bentley Motors Limited. The methodology carves out the functions to be implemented into a FRP part in order to exploit the full potential of composites and supports the decision between different potential materials. This leads to a new product architecture for an existing system, which considers the material specific requirements and properties. In the end, this methodology allows the designer to rethink a system without losing himself in a time consuming CAD design process.*

1 INTRODUCTION

"If you always do what you've always done, you will always get what you've always got!" This sentence, said by nobody less then Albert Einstein, pretty accurately describes the problem within large organization when it comes to innovations. Two Third of current innovations within Germany are material based [8] - so the big question is how to implement a new material into an existing structure? When it comes to designing with carbon fiber reinforced polymers (CFRP) the catchword "Black Metal" is often used to describe an insufficient design. Insufficient in this context might be a not fiber feasible design or even more accurate, a design where the material specific properties are not exploited to its full potential. According to Schuermann [4] the biggest problem when designing with FRP is that "Fiber reinforced polymers are considered as a material category, but are actually an engineering design". According to the AVK the fact that material with its properties is created during the manufacturing process, leads to a strong relation between the shape of the part, the manufacturing process, and the final properties of the material [6]. All this highlights a huge challenge, when designing with FRP. Within the automotive industry the two main drivers to implement a CFRP part within a design, is to achieve a unique selling point for the costumer by showing off carbon weave as a racing style, as much as the additional weight saving. This leads to the first challenge for CFRP parts. Where the unique selling point can be achieved by just using a decorative top layer, significant weight saving primarily depends on a good engineering design. Friedrich [7] and Henning et al. [8] highlight several different strategies for a comprehensive lightweight design, but both come to the conclusion that a fully integral design with a system approach is the best solution in order to gain substantial weight saving. This inevitably leads to the second big challenge for lightweight design within the automotive industry. How can you motivate an industry that is geared towards cost efficiency and hence high economies of scale, to rethink a system? Different OEM's have different ways of achieving these economies of scales, but a modulus design technique with several carry over parts from different products is state of the art for almost every car manufacturer. A real system approach for lightweight design is often impossible due to the boundary conditions. Most parts within a car are designed for plastic or metal manufacturing processes. Introducing a FRP part into an assembly and trying to make the existing product architecture form a symbiotic relationship with it, is almost impossible if you cannot align the other parts. This problem is intensified by the usual division into different departments like Body in White (BIW), Interior, Hardware, etc. Every department has their own functions and hence their own point of view onto a system and a change in one part usually increases the work for the other departments as well.

The two main objectives of this research are:

- Developing an objective design process to rethink a system without being held back by these "borders"
- To deliver a quick and easy way to alternate product architectures in consideration of the used material and the gained weight saving

This can only be achieved by simplifying a complex structure but not losing the important information. Thus this approach focuses on a high level design for a rough structure without going into too much detail.

In order to evaluate the new product architecture as well as the design process it is necessary to understand the requirements for both. For this case study the object of investigation is a frameless, full door system of a Bentley Continental GT. As an independent but still highly interdisciplinary system within the car it represents a perfect example of how this design process works and also allows the validation of the new product architecture.

The structure of this research is aligned onto the German standard VDI 2221 [1] which is directly or in variations the basis of most engineering design approaches taught and executed within Europe. In a first step the current design of the doors of the Bentley Continental GT have to be captured and the main functions have to be derived. It is important to distinguish between costumer and engineering functions in order to remain a stringent approach. In the next phase a tool developed by Albers and Matthiesen [2] called the channel and support model is introduced, which allows an easy and intuitive way of illustrating a product architecture and changing it, without going into a time consuming CAD-design process. Using this tool, the current state of the art of automotive door structures can be mapped. Although this research focuses on structural FRP systems it is important to understand and consider all available materials within a design process. According to Ashby [3], it is necessary to know the limiting load cases and the best suited material for the existing requirements. In the end a product architecture that creates a symbiotic relationship between every part and enables a huge function integration will result in an efficient design to fulfil the required functions and thus in a high weight saving.

2 METHOD

The key to an innovation is always to start without thinking in old patterns or old solutions. Thus it is important to define the functions and the requirements of the product in a neutral (solution free) way. It is also important to define if such a radical way is the correct approach. Reinventing the wheel is often insufficient and using old solutions is often far more practicable. For this research though, the introduction of a new material and hence a more radical innovation is the basis.

2.1. Design guidelines and lightweight strategies

According to Pahl et al. [9] it is very important to define a functional structure of the part in order to identify potential risks, define major functions, highlight potential modules and in the end map the product architecture. The full VDI-2221 [1] guideline can be seen in Figure 1.

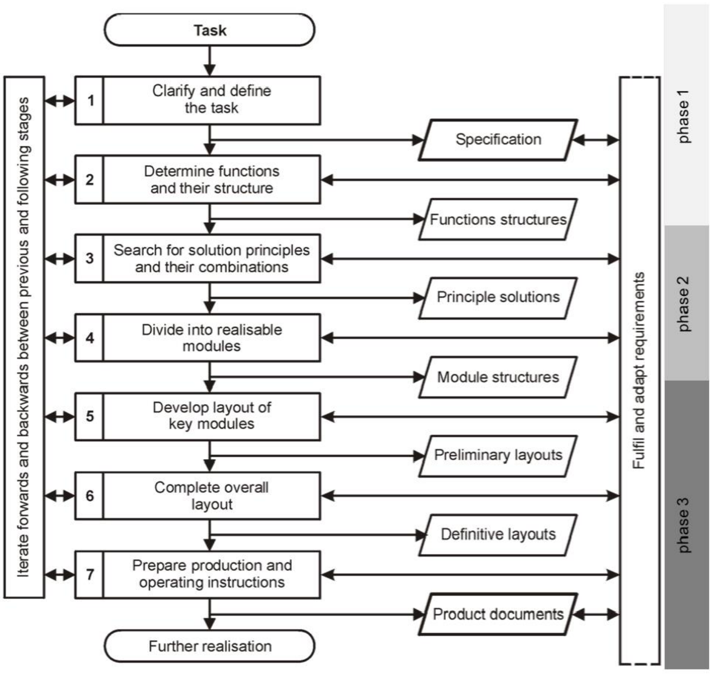

Figure 1: Development process according to VDI-2221 [1]

Considering the importance of a significant weight saving, when introducing FRP parts into a vehicle, it is also important to examine different lightweight strategies for automotive components. Friedrich [10] carves out 5 major lightweight strategies, which are also affirmed by Klein, Schindler, Schmidt and Henning et al. [11, 12, 13, 8].
They are:

Material lightweight design

Existing material is substituted with new lighter material with similar or even better mechanical properties. A weight saving is achieved fairly easy, but is often accompanied by a cost increase. As the part geometry was designed for the previous material or manufacturing technique, often the design needs to be optimized to make good use of the performance of the new material [11].

Shape lightweight design

Force flow and sections of force transition are optimized with FEA and topology optimization. By introducing more material in high load areas some material can be reduced in areas with small loads. Thus the geometry is optimized and the overall mass is reduced [12].

Conditional lightweight design

The loading conditions, boundaries and constraints for a part or a system in the relevant use cases are analyzed in order to identify oversized structures. The analysis questions the safety factors used for the design and the choice of material. In the next step the identified parts are redesigned and optimized to save weight [13].

Conceptual lightweight design

A system or an assembly consisting of several parts is analyzed whether the boundaries of the system or assembly can be extended or redefined in order to reduce the overall part count and improve the part design. Hereby weight savings are achieved through deleting joints and fixings between the parts [13].

Manufacturing lightweight design

Some geometrical features or elements of part are designed to achieve feasibility for a specific manufacturing process. This strategy tries to reduce the features which do not contribute to the function of the parts by optimizing or changing the manufacturing process. By deleting these features material mass is reduced and weight is saved [13].

The key to a comprehensive lightweight design however, according to Friedrich [10] and Henning et al. [8] is the combination of all strategies. Both highlight the importance of considering the whole car or assembly as a system where every part is influenced by each other. Every part contributes to the overall function and has to be taken into account during the lightweight design process. Where Henning et al. [8] see the system lightweight design as a part of the conceptual lightweight design, Friedrich [10] defines it as an superordinate part of the material and shape lightweight design. Nevertheless both agree that the key for a system approach is to understand where and how the different parts influence and interact with each other.

In order to enable a preferable neutral view onto a current door system and consider the whole door as a system an approach to combine the functional structure and product architecture is used. According to Goepfert and Tretow [9] the “METUS-Raute” fulfils these requirements. It allocates the different functions of a system to the specific parts within the assembly. Applied to a Bentley Continental GT door system the result can be seen in Figure 2. A list of how much every part contributes to the different functions is the basis of every line within the “Metus-Raute” and allocates the parts weight and cost to the different functions.

It is very important to distinguish between engineering and costumer functions. Where the engineer for example has to introduce new parts to ensure a tolerance compensation or fulfil legal requirements, the costumer is only interested into the door looking good and enter and exit the vehicle, everything else is assumed. Depending on how radical the new design should be the decision which functions are considered has to be made. Using the engineering functions will lead to a semi-radical new design, still delivering a significant weight saving.

Considering the costumer functions though will radically influence the new system and will lead to a totally new product architecture. Within this research the focus lies on the engineering functions.

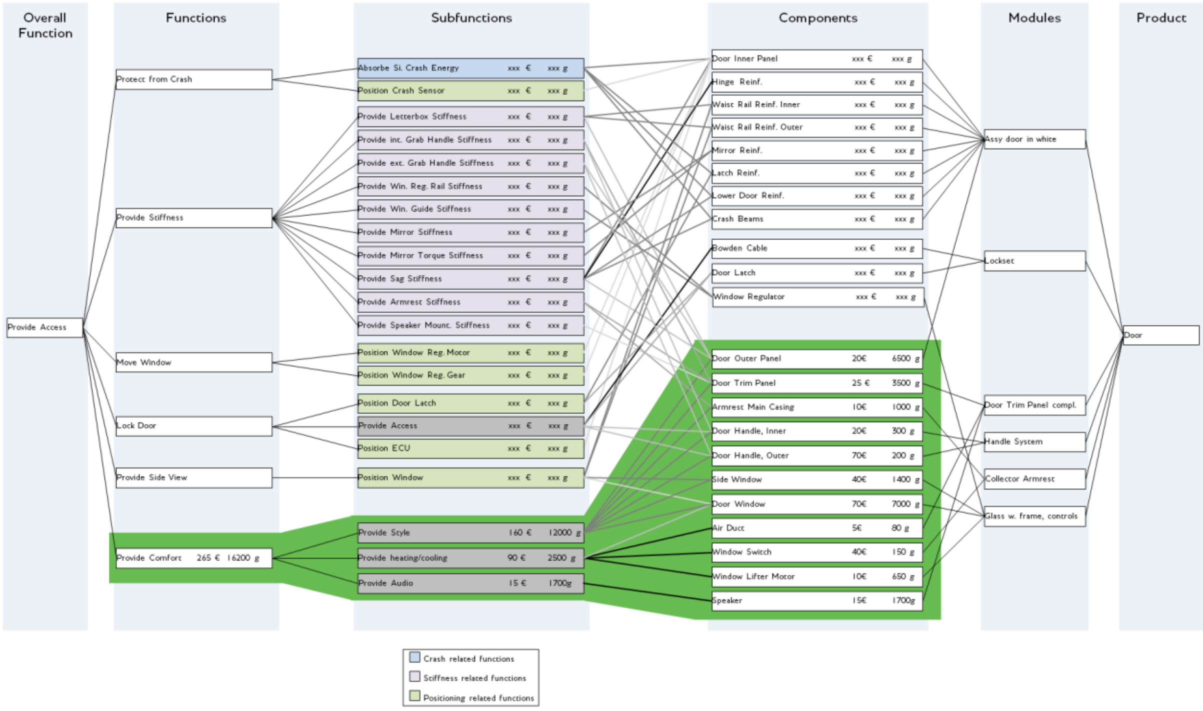

Figure 2: "METUS-Raute" of a Bentley Continental GT door (all figures are generic)

This approach also allows to allocate the costs and weights of the different parts to different functions (all data in Figure 2 is generic). These numbers give a first impression of which function is the main cost and weight driver. By integrating one main function into a new integral FRP part, higher unit costs can be justified and it allows a hollow cost and weight management.

When focusing on the structural relevant functions in Figure 2 it is striking, that all of them can be clustered into either crash related function, stiffness related functions or positioning related functions. These three attributes will form the basis of the next step of this design process.

2.2 Working surfaces and channel and support structures

The challenge after understanding the main functions of the door structure is to develop a new fiber feasible design that allows fast iteration steps if necessary on a high level (rough structure). The usual design process within almost every industry is currently very data driven. Using CAD-programs has revolutionized the automotive industry within the last years. However this does not come exclusively with advantages. The more complicated it is to learn and use a program the less cognitive capacity is left to externalize a thought [14]. A way to overcome this problem is to use working surfaces and a channel and support structure which were developed by Albers and Matthiesen [2]. According to Lemburg [14] and Benders [15] the biggest challenge for the redesign of a structural component is the second phase of the design process. The engineer needs do develop suitable solutions from an abstract level of a function structure to a concrete level of a module structure. According to Benders [15] the field of solutions is often limited by several factors:

- The correlation between geometry, shape and material often receives to little attention.
- The selection of possible material is often limited, as the engineer only considers materials he is familiar with.
- There is just a small number of methods and tools available to support the process.
- To use the methods and tools a special software is often required.

According to Albers and Matthiesen [2] the following definitions of the methodology are the basis of the next steps:

- <u>Working surfaces (WS)</u>
  Working surfaces are fixed surfaces of bodies or boundary surfaces of fluids, gases or fields, which are in temporary or constant contact with another working surface and which contribute to a flow of energy, flow of material or flow of information.
- <u>Working surface pair (WSP)</u>
  Working surface pairs are two working surfaces which are in temporary or constant contact and thereby transfer a flow of energy, flow of material or flow of information.
- <u>Boundary surface (BS)</u>
  Boundary surfaces are fixed surfaces of bodies or boundary surfaces of fluids, gases or fields, which are never working surfaces and which never contribute to a flow of energy, flow of material or flow of information.
- <u>Channel and support structure (CSS)</u>
  Channel and support structures are volumes of bodies, fluids gases or field-interfused spaces, which connect two working surfaces pairs and transfer continuously or occasionally energy, material or information between working surfaces of bodies or boundary surfaces of fluids, gases or fields.
- <u>Support structure</u>
  The support structure is the set of all possible channel and support structures.
- <u>Rest structure</u>
  Rest structures are volumes of bodies, fluids gases or field-interfused spaces, which cannot be channel and support structures.

With these basic elements, a technical system can be described without defining the embodiment of the system. It can be used to analyze but also to synthesize new products. It encourages the engineer to develop function based solutions, rather than part or shape based solutions. This enables the engineer to design completely new structures and thereby supports an optimized design with new materials.

The working surfaces for a door structure are primarily defined by the hinges (link to BIW), the latch and the seals, all mounting parts and by the A-Surface which is provided by the styling department. Including all working surfaces in one view however, leads to an overloaded picture and is the opposite of the methods intention. Hence, a clustering off all working surfaces and their CSS into their functional area has proven itself to be very effective. These three areas are crash related functions, stiffness related functions and positioning related functions. Thus a function-centered view on the system is created which allows an easy and quick way to understand a system. This approach is used to conduct a market analysis which is shown in Figure 3 in a simplified way.

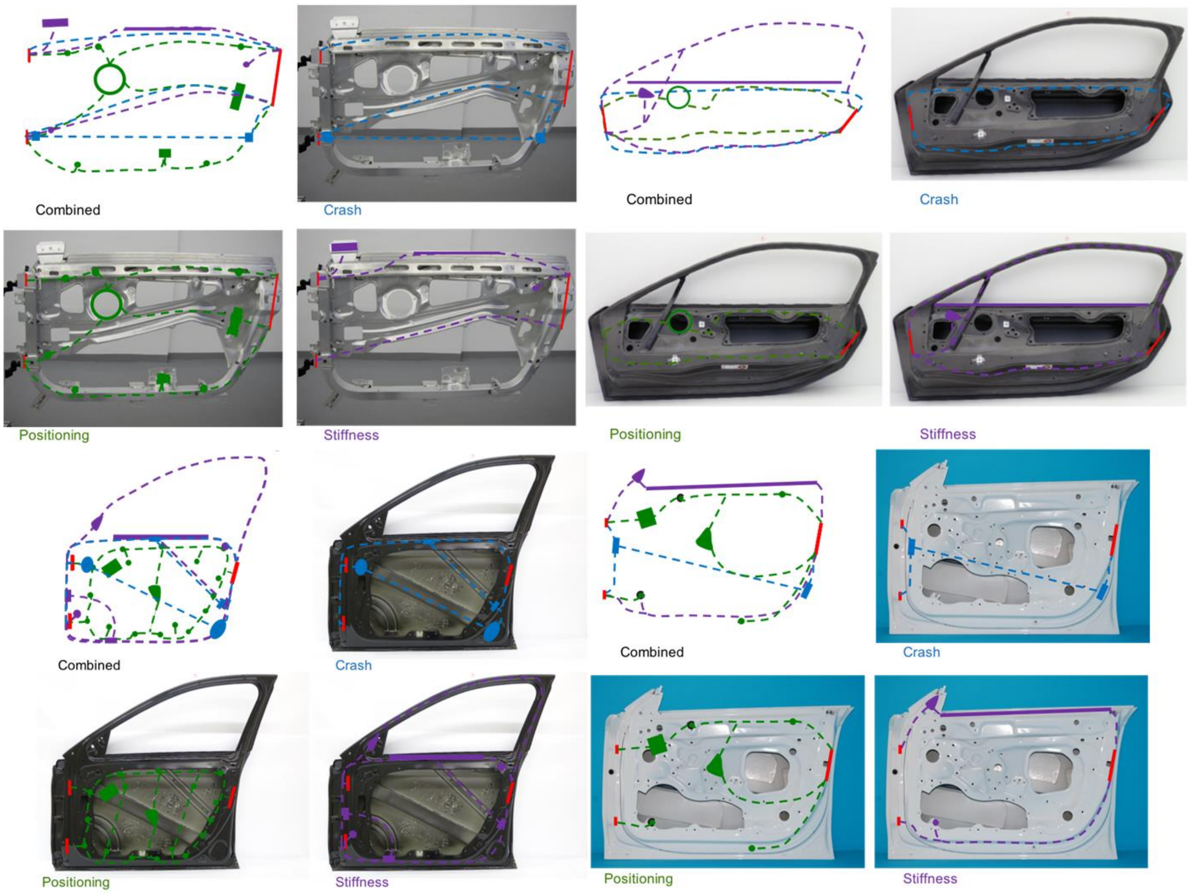

Figure 3: Clustered Channel and Support structures of BMW i3, BMW i8, Mercedes S 550 L and Audi A7 Sportsback (left to right and top down)

These three main functions highly correlate with different material properties. Where the main design criterion for crash properties is the tensile strength, stiffness properties are represented by the Young's modulus and for positioning related functions the freedom of design and hence often the manufacturing technique is relevant. With these information and the forces on the system, it is possible to use the CSS to derive a new product architecture incl. cross sections for the different modules.

2.3 Concept ideation

On basis of the design relevant working surfaces new potential channel and support structures can be generated. It is recommended to develop these CSS in a multidisciplinary group (quality, manufacturing, etc.) in order to understand the impact on the whole system. This rough structure can be drawn on a piece of paper or supported by simple splines in a CAD-system. The process can be seen in Figure 4 for the function "Absorb Side Crash Force". Depending on different fixing strategies the main load paths can be alternated. Although a direct load path through the system is preferable [9] sometimes introducing an indirect load path is more feasible due to the used material or boundary conditions.

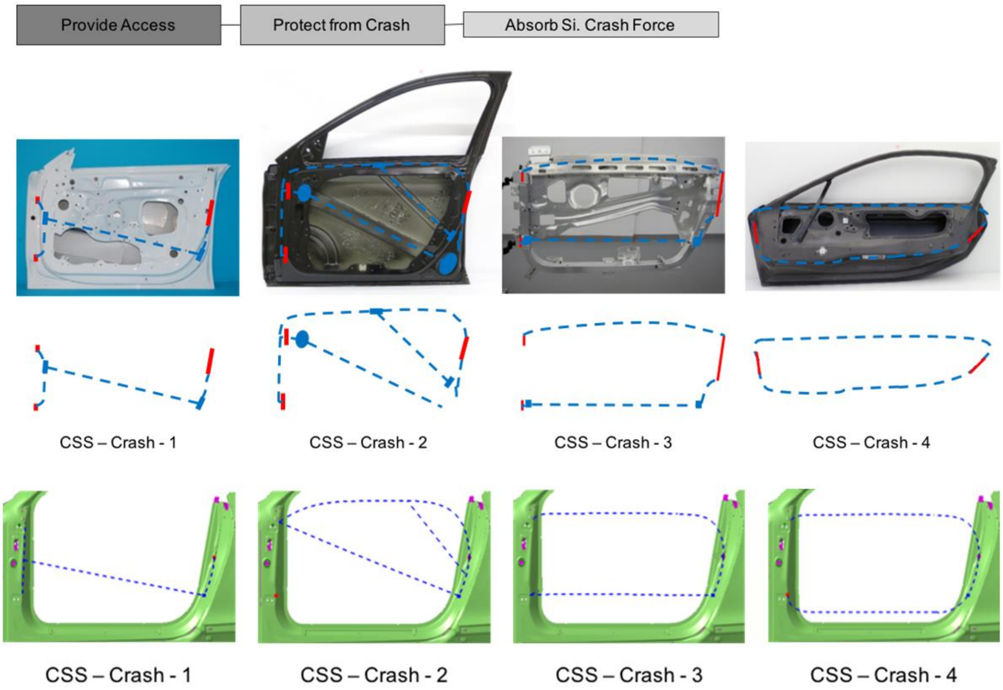

Figure 4: Transfer new CSS analysis into the CAD model

Within this research a first concept for the door module is developed by separating all load bearing working surfaces and by integrating them into one module. This leads to a very efficient CFRP part in regard of weight and costs. A second concept includes most of the structural design relevant functions in one module and thereby reduces the overall part count. The third concept introduces a frame structure which carries most of the attached parts and creates the required stiffness for the working surfaces in the interior. Including the working surfaces of the interior also delivers a bigger cross section and hence a stiffer system behavior. On the basis of these rough concepts the embodiment design has to be conducted. The next step is to find different possible cross sections for each CSS. This decision however, cannot be made independently of the material, the fixing strategy and the load cases. According to Feldhusen [9], a design process should be solution free as long as possible. Benders [15] recommends to make a decision on the cross section, then decide which manufacturing process can deliver that shape and then choose a material. In order to combine different solutions and compare them regarding cost, weight saving and risks a structured way has to be defined. Within this study two different approaches are preferred. The first approach is based on the design process for lightweight structures with CFRP-metal hybrid design. Hufenbach et al. [4] suggest to develop a bearing structure on the base of the load cases and the design space. The second approach to develop cross sections is based on Ashby [3]. According to Ashby [3], cross sections to which a material can be formed are limited by the processability and mechanical behavior of itself. To develop the best shape for a part, Ashby [3] suggest to investigate the shape efficiency of a cross section.

The following steps of the design process cannot be described for each module of each concept within this study. Therefore, the process is examined and described for one sample module of concept two. In order to facilitate the perception of the process, the geometries of the module are simplified to a certain degree. In the concept ideation the modules are defined by allocating the different channel and support structures to them. Figure 5 depicts the different steps from the CSS to a construction space. Working surfaces and channel and support structures, derived from the structural functions, which have to be fulfilled by module 2 are shown in the middle picture of Figure 5. To establish an integral door, the modules have to be attached to each other. Therefore, working surfaces are created which define the joints between the modules. The position of the working surfaces is defined through the concept ideation. The shape is roughly derived from the given design space and will be detailed in the later design process.

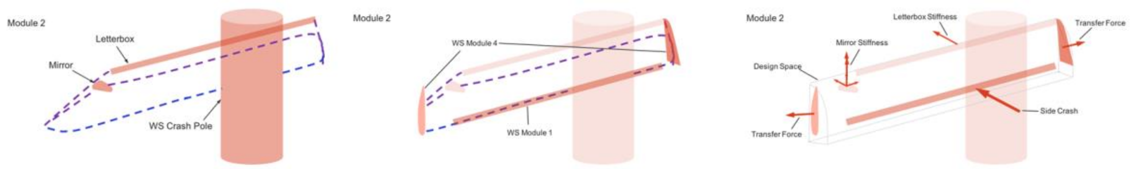

Figure 5: Steps from a CSS to a constructing space

According to Huffenbach [4], the bearing structure can be transformed into a quantifiable model which helps to develop a fiber feasible design. Since the load cases and the design space are already defined for the module, the bearing structure can be directly established. The bearing structure for module 2 is depicted in Figure 6. All points in which force is applied are considered as nodes. The nodes are connected with beams or belts to establish the bearing structure. The areas between the beams are considered as shear areas. In the following process, the model can be used to determine the layup for a fiber reinforced material. The process is shown in the right picture of Figure 6. The force transmission through the beams can be realized with axial fiber reinforced in a 0° angle. The shear areas can be supporting fibers in a 45° angle along to the force flow. To ensure a steady force introduction into the fibers, a force transmission element has to be designed alongside the fiber orientation. With this simple first layup a rough weight and cost estimations allow an objective comparison of different concepts. This also enables the designer to compare different fibers and resins in dependence of the forces and the rough layup.

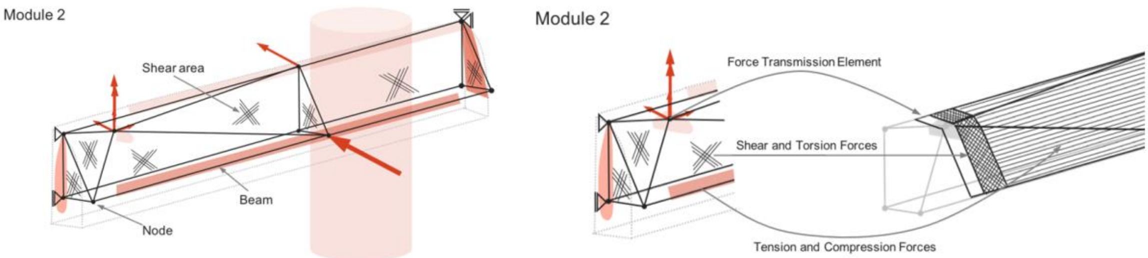

Figure 6: Load bearing structure of Module 2 (left picture) and definition of a FRP layup based on the bearing structure (right picture)

The second approach to develop cross sections is based on the Ashby method. According to Ashby, cross sections to which a material can be formed are limited by the process ability and mechanical behavior of itself [3]. To develop best shape for a part, Ashby [3] suggests investigating the shape efficiency of a cross section. For a static analysis, the given load cases for the module can often be summed up to four main modes tension, bending, twisting and compression.

The main load mode is used as the design criteria and with the help of the mechanical context a shape efficiency factor is developed. On the basis of the shape efficiency factors, different shapes of cross sections are developed and compared with each other. Hence, the best shape for the cross section is determined. If one main load mode cannot be identified, a combined equation of shape efficiency factors can be defined which then can be differentiated to find the best solution. Once the framework is established, a comparison with different materials, meaning different Young’s moduli, can be performed.

3 RESULTS

After developing cross sections for each module, all solutions for each module are filled into a morphological matrix. This matrix helps to determine all possible combinations of the modules and hence line out all possible design options for the concept. To evaluate whether different modules are combinable, two factors are considered. One factor is how the shape of one module fits to the shape of the adjacent module. The second factor is the fixing strategy between two adjacent modules. This is evaluated in terms of material options, meaning feasibility of bonding between materials and in terms of force transfer through potential joints. Therefore, the possible options for the joints or fixture are also listed in the morphological matrix.

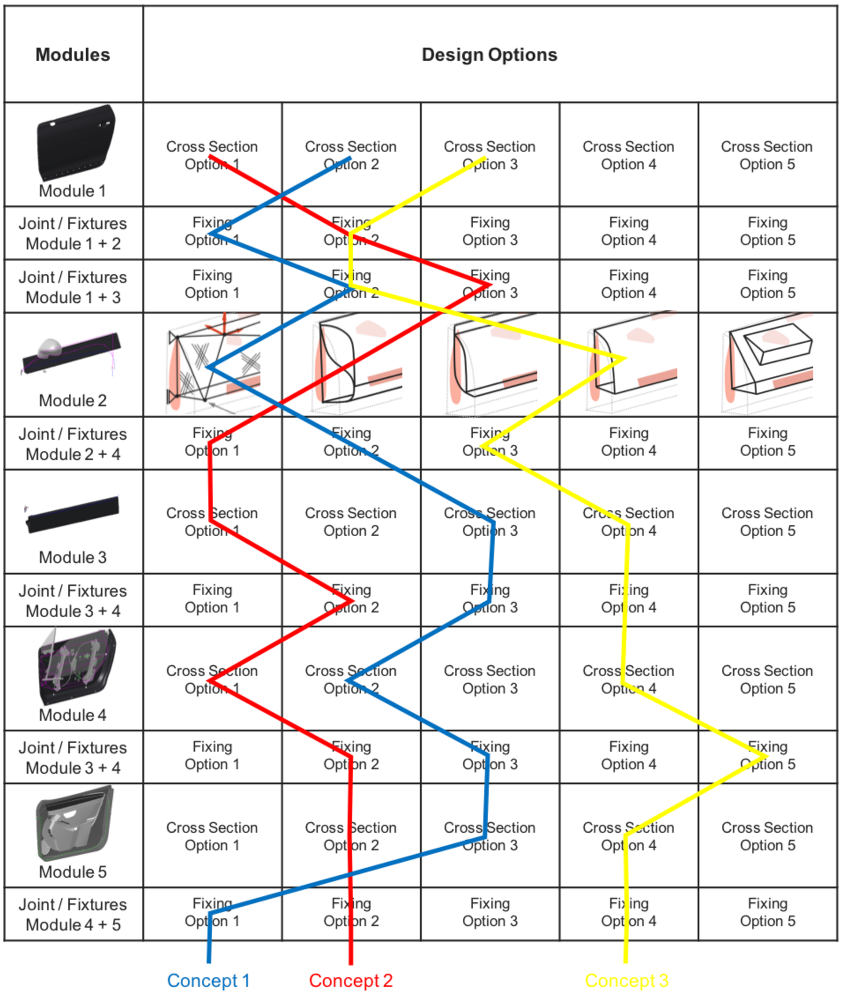

Figure 7: Morphological Matrix for concept selection

Depending on the options and the general structure, several combinations of modules and joining or fixing strategies are possible. A catalogue listing all possible fixing strategies for different material combinations in dependence of the load that has to be transferred is highly recommended for this design step. As a result, the morphological matrix delivers different concept options. To preselect concepts for the final selection, an assessment of the structural performance can be executed with a high level FEA. After the pre-selection, a small number of different structural concepts is available for the final concept selection. At this point, the design strategy and the rough shape of all modules are set for each concept. Potential options for material (fibers, resin, etc.) and joining or fixing of the modules are in place. Further the potential of integrating new technologies and innovations can be defined for each concept.

The final concept which is chosen in the end lead to a weight reduction of 32%. This was possible due to a part reduction and a material substitution from aluminum and PC/ABS to CFRP.

4 CONCLUSIONS

The current research project shows, that a system lightweight design is superior towards a “simple” material substitution. The challenge however, is to develop different concepts, considering all the parts of an assembly as a whole system that influence each other. Especially when designing with FRP the impact of different manufacturing techniques, fibers, resins and shapes is very high onto the properties of the finished part and seldom considered during the embodiment design. With the introduction of the methodology based on the contact and channel model and a function-centered view on the system a pragmatic but still comprehensive solution is developed. It inspires to rethink a system despite of different departments or former parts without going into a time consuming CAD-design process in the early stages of the development. The process encourages to stay solution free as long as possible and by doing so opening the possibility to think outside the box. Despite all the advantages of the new process, it is important to evaluate how significant the changes for a new vehicle should be. In order to maintain the aspired economies of scale a modulus design technique for a new derivate might be more feasible. For the concept development of a new car this new design process however offers a lot of advantages.

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