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MULTI-CRITERIA ANALYSIS OF MULTI-MATERIAL LIGHTWEIGHT COMPONENTS ON A CONCEPTUAL LEVEL OF DETAIL

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Abstract

Multi-material design offers higher degrees of freedom in designing a component due to different design options and material combinations. However, both cause a more complex component design. In addition many development goals - such as weight, costs and environmental impact - and outer conditions - such as restricted installation spaces - have already to be considered in the early stage of development. Otherwise the most suitable design option might not be considered and concepts are no longer pursued after design in detail since they did not fit the requirements from the beginning. As a result, the designer needs assistance in analysing different design options to find those that are able to fulfil the development goals best possible within an appropriate effort. A suitable approach to solve this issue is to represent the considered component by an abstract definition and calculate the component's properties analytically inside an automated tool. Thus the general behaviour of a design option and specific variations can be evaluated by the designer. Consequently components can be designed more purposeful considering a big solution space and a variety of development goals.

Keywords: Conceptual design, Early design phases, Design methodology, Multi-material design, Multi-criteria analysis

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1 INTRODUCTION

The weight of vehicles has consequently increased in the last decades to fit the costumers' growing needs regarding comfort, safety and entertainment. On the contrary, laws regarding CO2-emissions and therefore, fuel consumption have tightened (Nehuis et al., 2014).

Beside advanced engine and drive technologies the reduction of the vehicle's weight by lightweight design is the most promising approach to fulfil these opposing requirements. Nowadays, economic reasons prevent the use of lightweight materials for large scale production. High costs, large environmental impacts as well as expensive manufacturing of fibre-reinforced plastics (FRP) and especially carbon fibre reinforced plastics (CFRP) limit the application of these materials to top-of-the-range vehicles.

Because of that, only a usage- and load-confirming application of these materials leads to promising lightweight concepts. This approach is pursued by multi-material design which combines both high performance lightweight materials and conventional materials in a single component. Consequently, multi-material design enables the application of lightweight materials in large scale production as well (Täger et al., 2013).

While designing vehicle components many development goals have to be considered. The major goals are weight, mechanical performance - for instance stiffness, strength and crashworthiness - costs and environmental impacts. Decisions made in this conceptual stage have great influence on the final component thus all development goals have to be considered in an early stage of component development. Furthermore, the increased number of materials which can be combined in a single component lead to a higher degree of freedom in designing the multi-material component. As a result the solution space of concepts is increasing as well, which leads to a higher effort in considering the possible design options. Determining the necessary properties for a comprehensive evaluation is very time- and resource-consuming especially considering the whole possible design space. As a result the entire design space is not considered and promising approaches are not pursued or not all development goals are considered from the beginning.

Due to missing expert knowledge regarding lightweight materials and multi-material design in general, the designer needs support in understanding the opportunities and limitations of different design options. Kleemann et al. (2016) show one approach towards supporting the designer by knowledge based engineering.

To basically understand different design options, detailed geometries are not expedient. A comparison on an abstract level of detail enables the designer to focus the general differences e.g. concerning mechanical performance and thus necessary size of cross-section and wall thicknesses, weight, costs as well as environmental impact.

Consequently, less time-consuming methods and tools are necessary which support the designer in selecting promising and deselecting unfitting design approaches in an early stage of development. In this way the resulting component has an increased quality due to a more promising design option and more resources spent for design in detail.

2 CONCEPTUAL MULTI-MATERIAL DESIGN

2.1 Developing multi-material components

Nowadays, the development of automotive components follows a strict process in which the development goals for every component and the available installation space is defined in a very early stage of vehicle development. So the boundary conditions are already defined before the actual component design starts (Weber et al., 2009 and Kaluza et al., 2016). A verification and validation is done subsequent to the component development in order to analyse if the superordinate system and the entire vehicle fulfils the development goals. This process is illustrated in Figure 1 by Kaiser et al. (2016) adapted from Mayer-Bachmann (2008).

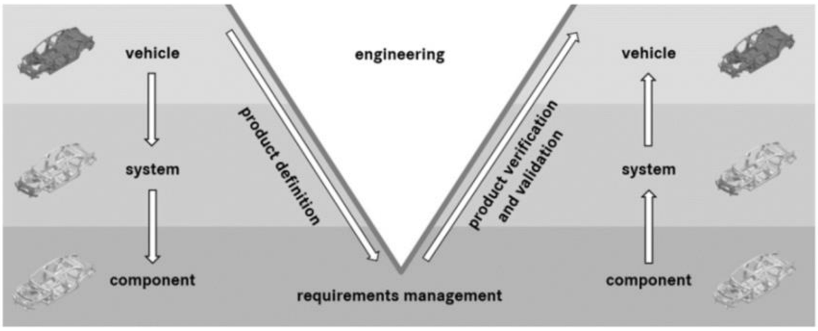


Figure 1. The V-model on the basis of the vehicle development after Kaiser et al. (2016) adapted from Mayer-Bachmann (2008)

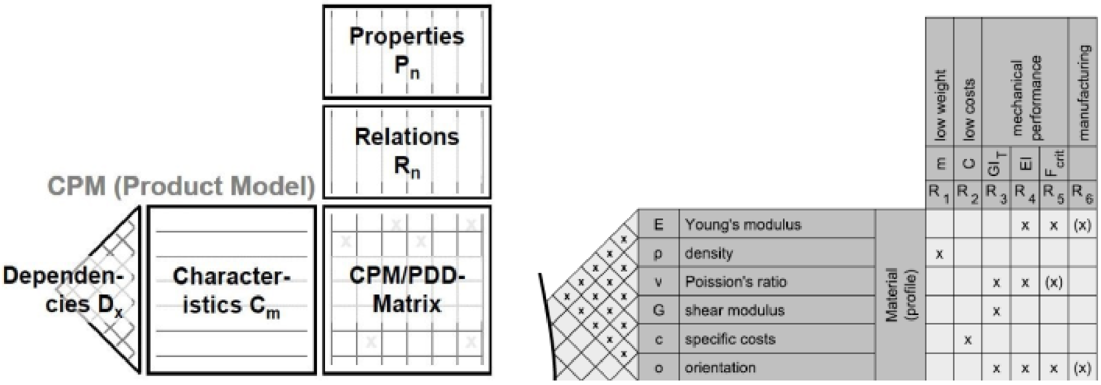
Therefore, in many development tasks the installation space of the component is fixed and cannot be increased due to adjacent components. This leads to limitations regarding the component design by using lightweight materials. Since, what is necessary for the application of lightweight materials - e.g. aluminium - instead of steel, are an increased wall thickness or increased cross-sections to reach the mechanical performance of a steel component. Consequently, the installation space might not be sufficient to reach the demanded development goals by substituting one material by another. An application of e.g. CFRP might reduce the components weight whereas costs and environmental impact is increased as shown by Duflou et al. (2009) and Song et al. (2009).

As a result, different design options have to be considered in order to fulfil the development goals as good as possible, especially in terms of solving goal conflicts and reduce compromises. Due to the considerable differences between the behaviour of different design options and possibly missing expert knowledge, what seems to be expedient, is a basic analysis of different design options. This leads to an understanding of the design and thus explains the designer how to influence the component's properties.

2.2 Properties and characteristics

As the component's properties - like weight or costs - can only indirectly be defined by characteristics - like dimensions or material - (Weber, 2012), the relations between properties and characteristics have to be exposed in order to identify the scope of influence on the properties by the designer.

One approach to structure those relations is the Property Driven Development (CPM/PDD) by Weber (2007) that was extended by a matrix representation by Köhler (2008). This matrix maps the interdependencies and relations between characteristics and properties as well as the dependencies between characteristics as shown in Figure 2 (left).



			low weight	low costs	mechanical performance			manufacturing
			m	C	GI_T	EI	F_{crit}	
			R_1	R_2	R_3	R_4	R_5	R_6
E	Young's modulus	Material (profile)				x	x	(x)
ρ	density		x					
ν	Poission's ratio				x	x	(x)	
G	shear modulus				x			
c	specific costs			x				
o	orientation				x	x	x	(x)

Figure 2. Matrix representation of CPM/PDD approach (left) after Köhler et al. (2008) and application with detailed focus on material parameters (right) after Kleemann et al. (2017)

This approach is useful to structure relations, however the magnitude of relation cannot be represented in a sufficient way. In addition, a general consideration of relations does not give enough information because on an abstract level every characteristic - such as *material* - influences every property. Therefore, the characteristics have to be more detailed and thus specific for every design approach. Especially for material selection an analysis of the specific material parameters is necessary as done by Kleemann et al (2017). Figure 2 (right) gives an extended view on the different relations for a U-shaped profile with cross ribs and a small amount of properties with focus on the detailed consideration of material parameters.

A basic comparison of different design options by creating mapping matrices for each concept does not seem to be expedient considering the effort. However, the modular structure of the mapping matrix enables the combination of prepared modules - such as material parameters - and thus has potential in modelling abstract component concepts.

As the CPM/PDD approach respectively the mapping matrix does not give any assistance in determining the properties' values, they have to be quantified separately. One way of quantifying the properties' values is an analytical calculation by e.g. spreadsheet programs or computer algebra systems. Admittedly, especially mechanical properties can only be determined by a simplified calculation and thus - in comparison with for example numerical analysis like FEM - with a limited accuracy. However, the advantage of an analytical calculation is automation, reproducibility and that it can be used in considering nearly every problem.

2.3 Material and geometry selection

Since the demanded functions of a component can only be realised by the combination of material and geometry, the selection of material is a major task in component design. There are many approaches of finding suitable materials given e.g. by key performance indicators (*Gütekennzahlen*) (Klein, 2013), material-indices or Ashby-charts (Ashby, 2010). An overview of material section methods is given for example by Ashby et al. (2004) or Jahan et al. (2010).

Methods for material selection mainly take into account a limited quantity of criteria. Due to the amount of development goals, a multi-criteria analysis for identifying suitable materials is necessary. In addition, when using multi-material design, not only one material has to be identified, but two or more materials. As the potential of multi-material design only comes into effect by considering not every material separately but the combination of materials, material selection is getting even more complex. An approach for material selection especially in multi-material design is given by Giaccobi et al. (2010).

Based on the general consideration, the shown approaches are not taking into account the component's geometry or restrictions such as a limited installation space as necessary. As those restrictions highly influence material selection, an approach for considering those aspects is given by Wanner et al. (2010) in case of limited available space on a simplified geometry. But by changing the design approach or extending the installation space by redesigning more than one component, the specific geometry of the component is unknown, as well. Thus suitable materials and geometries have to be identified in combination taking into account the interference between both.

Furthermore, the transferability of the selection to the specific problem still has to be validated in subsequent complex simulations such as FEA as the selection bases on a general consideration - e.g. simplified load cases or cross sections. Consequently, a first validation of the material and geometry selection has to be considered within the method. Those fast analysis tools for example are used in aeronautic engineering for multi-disciplinary preliminary design of an aircraft body (Ciampa et al., 2013). Koschorrek (2007) has shown an approach of dimensioning automotive components in an early design stage by similitude analysis.

Consequently, adapting these approaches to multi-material design considering multiple development goals seems to be a promising assistance. Thus an analytical validation of design options according to the specific problem can be realised for an early decision making and dimensioning.

3 METHODOLOGY

This research aims at developing a tool to support the designer in the identification of promising design options on a conceptual level of detail. Therefore, an evaluation based on an abstract component definition was realised. In preparation of implementing the tool, four major views on the task relating to Türck (2016) have been considered:

1. Conflict view: identifying relevant requirements and thus evaluation criteria on the component.
2. Component view: defining the component in an abstract way regarding the necessary characteristics.
3. Process view: defining the evaluation process of components regarding the designer's requirements.
4. Tool view: designing the tool regarding its structure, automation and user interaction.

In this research the identification of requirements and the translation to evaluation criteria is focused as well as the determination of an abstract component representation.

3.1 Conflict view

Many requirements have already to be considered in the creation of concepts. A solely consideration in later stages of development may lead to numerous changes, because the already detailed component did not fit the requirements from the beginning. The major requirements in body component design are the component's weight, mechanical performance, costs and environmental impact. An overview of requirements is given for example by Braess et al. (2003) especially taking into account resulting goal conflicts.

But not the entire amount of requirements can be considered in the early stage of development. On the one hand because this overextension would not lead to a result by a suitable effort. On the other hand many requirements cannot be considered because they refer to details which have not been defined in this stage, yet. Two examples for this issue are the crashworthiness - that can only be determined taking into account the whole vehicle system - and the component's stability - that highly depends on the detailed shape. Therefore, suitable requirements were identified and translated into evaluation criteria that can be evaluated in an early stage. Figure 3 illustrates the resulting hierarchical structure of the subgoals, which contain the related criteria. The subgoal *stiffness* for example covers the stiffness of the component through tension/compression, bending and torsion that can be considered individually according to the demands.

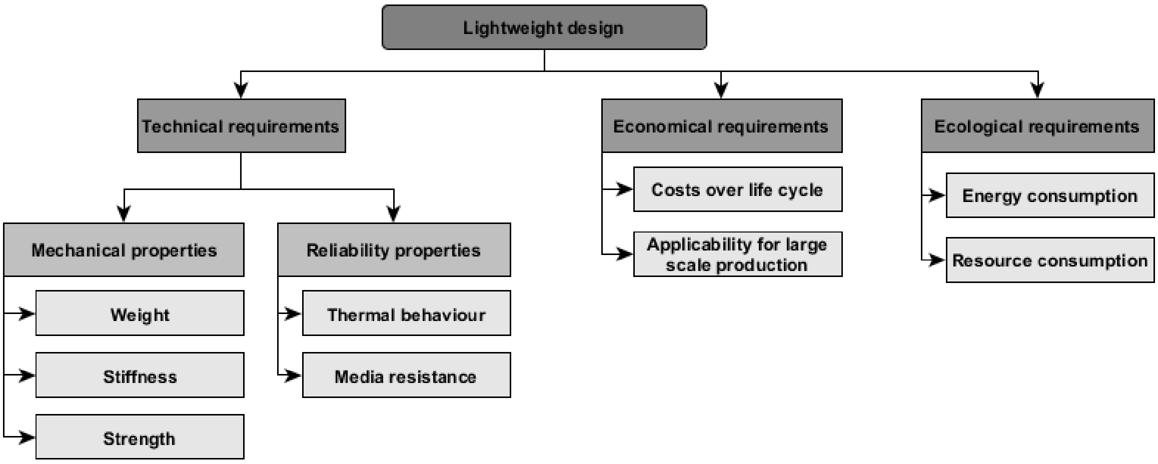


Figure 3. Considered evaluation criteria on subgoal level

In order to identify the characteristics which influence the selected properties and thus are necessary to be defined in the subsequent definition of components, the relations between the properties and the characteristics were identified. The generalised system of relations is shown in Figure 4.

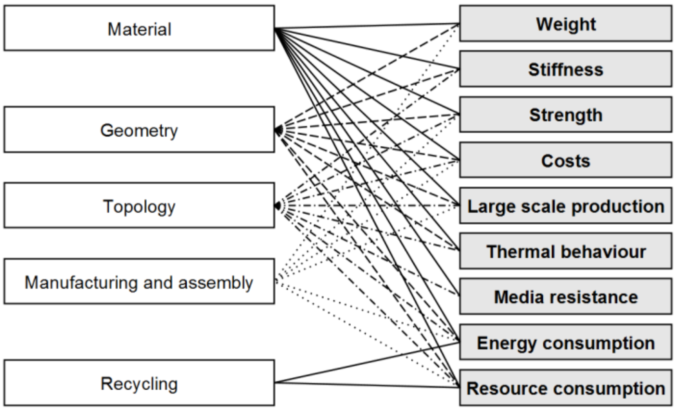


Figure 4. General system of relations

3.2 Component view

After the necessary characteristics have been exposed by the system of relations, the definition of components could be modelled. In order to represent as many components as possible and to take into account the early stage of development, the definition of components was done considering a preferably abstract level of detail. Admittedly, this approach only allows a relative and not an absolute analysis of different approaches, however in order to compare different design options to a reference or among themselves this approach seems to be suitable.

As every single material and related geometry has to be determined, the component is subdivided to separate elements which can be defined individually and combined to a component. The definition of component is done on two levels which are illustrated in Figure 5. On the element level every individual element can be defined separately in case of its geometry, material, manufacturing process and recycling. On the component level the topology, assembly and separation of elements is defined as well as the joining with other components.

Element level				Component level			
Geometry	Material	Manufacturing	Recycling	Topology	Joning of elemens	Joning with other components	Separation of materials

Figure 5. Definitions made on element level and component level

Most of the automotive components can abstractly be represented by generic geometries in order to identify suitable design approaches respectively material selections. Figure 6 illustrates this representation on exemplary vehicle components and generalised geometries. This approach was also used by Kellner (2013) to identify suitable design options taking into account the specific requirements of different body components. This approach was verified in a subsequent application of the identified design options on the components. Therefore, the definition of generalised geometries in order to represent body components seemed to be a promising approach and thus was implemented for the tool.

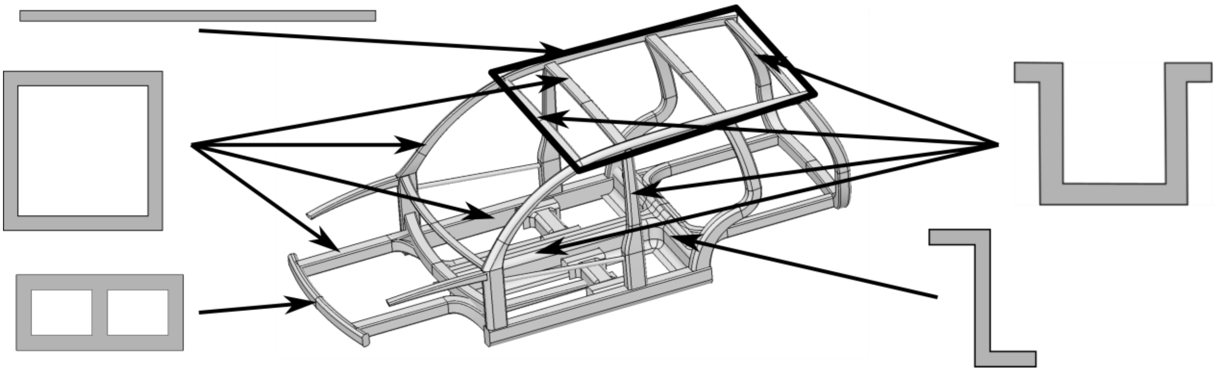


Figure 6. Exemplary representation of body components by generalised geometries

Admittedly, not every component might be sufficiently describable by these definition. It is mostly suitable to describe planar or profile-type components. However, in order to fundamentally analyse different design options this approach seems to be sufficient.

As the material is essential for generating the component's function, it influences each property of the component (Figure 3) depending on the specific parameters. Since the individual parameters cannot be changed separately but only by changing the entire material and thus all other parameters, they were clustered in characteristic groups with similar behaviour - metals, plastics, fibre-reinforced plastics. As ceramics are only applied in special applications, they are not considered within this approach.

On the one hand this clustering assists the designer in choosing suitable materials for specific applications. On the other hand it is necessary due to the difference of parameters which have to be defined. FRP for example have an anisotropic behaviour and thus most of the parameters have to be defined both in and transverse to the fibre direction.

Since FRP are mostly applied as multi-layer composite, a simple selection of material is not sufficient but every layer has to be defined individually. Although failure criteria of FRP - such as delamination - can be calculated by the tool, the analysis of multi-layer composites is done without taking them into account. Admittedly, they are of great significance in the assessment of the components, however, they highly depend on the detailed shape of the component and thus an analysis of failure criteria is not expedient for this approach.

For calculating e.g. the components stiffness and strength, the topology of the elements building the component had to be defined. Therefore, a coupling definition was chosen in order to determine the elements assembly. The coupling can be defined as series coupling, parallel coupling or a combination of both. Subsequently, the elements are arranged in the order defined in the coupling definition either horizontally or vertically.

As the manufacturing, assembly and recycling can be considered by their specific parameters - such as energy consumption, degree of raw material utilisation, costs or additional weight - the implementation was realised by the definition of the individual manufacturing and recycling process for each element as well as the assembly and separation process for each junction of elements.

Since the different process parameters are as individual as the material parameters, the definition of distinct processes and materials by the user was realised in addition to predefined processes and materials.

4 CASE STUDY

In order to demonstrate the application of the tool a case study is performed considering a substitution of a steel component by a lightweight concept at equal bending stiffness. The reference component is a generic hollow profile as it is applied e.g. as a body cross member in various positions. As the installation space of the cross member is fixed due to adjacent components, the dimension limits must not be exceeded. For a better transparency, the wall thicknesses are constant across the entire cross section.

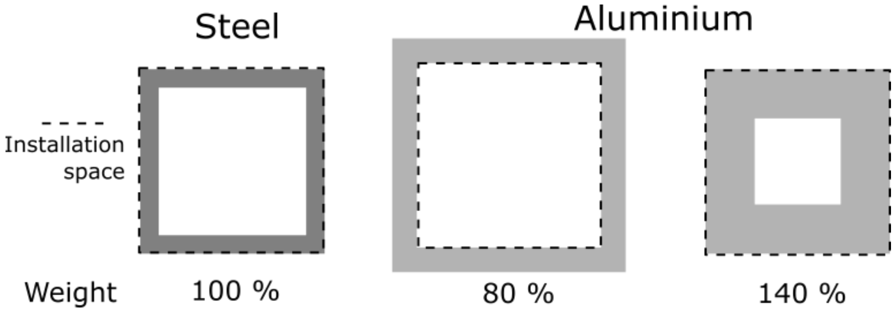


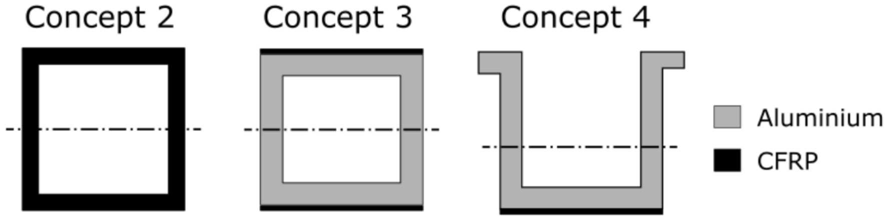
Figure 7. Aluminium substitution with increased and retained cross section considering the relative weight

The first concept is a substitution of steel by aluminium. As aluminium allows an increased cross section by bigger wall thicknesses, the weight of the cross member can be reduced at equal bending stiffness (Figure 7). Due to the limitation of dimensions, the cross section has to be retained and the wall thickness can only be enlarged towards the centre and thus the neutral fibre. As a result the cross member's weight is higher than the reference's weight. Consequently this concept is not applicable to substitute the steel component. Therefore, alternative concepts have to be considered. As not only the concept's weight is required in order to find an applicable solution, the concept's costs an Energy consumption - of the material and manufacturing/assembly process - are considered.

Due to the higher Young's Modulus and a lower density of CFRP - depending on the specification - compared to aluminium, the second concept is a CFRP substitution. This leads to a high reduction of weight, whereas the environmental impact and the costs are much higher (Figure 8). Consequently a CFRP substitution does not lead to a sufficient concept as well. For this purpose a multi-material solution is developed which combines the positive aspects of both materials and reduces the negative aspects.

The result is an aluminium hollow profile that is reinforced by CFRP tapes on the top and the bottom at maximum distance to the neutral fibre (concept 3). Additionally the type of the cross section is changed to examine the effect of geometry. Therefore, a U-profile is analysed as well (concept 4).

Figure 8 shows the results in terms of weight, costs and energy consumption at equal bending stiffness calculated by the tool. The reinforcement of the aluminium hollow profile by CFRP tapes leads to a significant reduction of wall thickness and thus a reduction of weight in comparison to the reference. By contrast costs and energy consumption have increased, however in comparison to the CFRP profile it is a more balanced solution.



Weight	31 %	54 %	69 %
Costs	460 %	230 %	285 %
Energy	468 %	296 %	345 %

Figure 8. Investigated concepts and their properties in relation to the reference

In comparison to the hollow profile the U-profile is worse in each criterion. Due to the single vertical flange and thus the shorter distance of the flange to the neutral fibre, the profile's stiffness is less and thus the wall thickness has to be increased. However, the advantage of the U-profile is its open shape. Therefore, additional actions can be taken to increase the stiffness and thus reduce the component's weight like cross ribs. Consequently, additional analyses have to be done to exploit the profile's full potential.

Further on, the designer has the opportunity to change e.g. the amount of CFRP of the concepts in order to reduce the costs and energy consumption by a simultaneous increase of weight or the other way round. These parameter studies can be done in the tool as well to examine the opportunities of a concept. If no of the considered concepts is able to fulfil the requirements, additional analyses might be necessary taking into account an increased solution space. Since the installation space is predefined by the vehicle definition, the issue of an increased installation space can be regarded in the vehicle definition.

An FE analysis of a cross member using the discussed design options has shown a good correlation to the proportions shown in Figure 8. The transferability of the accuracy to other components which geometry differ more from the generic geometries has to be verified in diverse subsequent analysis in order to define the approach's limits.

As one can see, many analyses have to be done to find the best solution whereby only a small amount of design options and development goals have been considered within this case study. This amount of analyses is not feasible to be done on detailed components with every property defined separately. Consequently, this approach enables the designer to analyse and directly compare a variety of design options and specific variations for multiple criteria simultaneously. An assistance in finding appropriate design solutions can be implemented by including other tools to the analysis process like design rules or specific multi-material design catalogues to provide a comprehensive tool chain to the designer.

The most promising solution chosen by the tool might not necessarily be the most promising solution for the final component. There are many other aspects which have to be considered by the designer as organisational aspects - e.g. available bonding and manufacturing techniques - specific failure - e.g. of the bonding layer - or the connection of additional components - e.g. brackets for electronical components - which cannot be considered by the tool. In addition, the effect of the assembled component can only be identified by an analysis of the overall system - e.g. the assembly group or the body in white - as the systems overall properties depend on the interaction of the included components. However the designer is supported in identifying essential properties of the component's concepts and thus can reduce the solution space more efficiently respectively focus on aspects which cannot automatically be determined.

5 DISCUSSION

Since multi-material design increases the opportunities and thus the solution space, an intuitive decision making is getting more difficult. Therefore, it is necessary to analyse general design options. The developed approach seems to be an appropriate solution estimating the potential of different design options. Thus the concepts can easily be analysed according to multiple requirements in an early stage of development.

Due to the limitations concerning geometry definitions, mainly planar or profile-type components can be represented. On the one hand many components can be represented by means of this definition in an abstract way. On the other hand more complex geometries and especially cast components cannot be represented sufficiently. Therefore, a connection to CAD is currently in trial phase in order to analyse the components weight, costs and environmental impact. However, by using this approach some properties - such as strength - might not be determinable anymore and thus both approaches are not entirely combinable.

Currently the definition of elements for each component is limited due to the coupling definition. As a positioning of the different elements is necessary for calculating the components stiffness or strength, the elements are stacked either horizontally or vertically centred. An individual positioning for representing individual components is not possible. This is why components such as a foam filled U-shape profiles or profiles with cross ribs cannot be properly represented inside the tool, yet. Therefore, a predefinition of common components taking into account the specific positioning of elements is prepared.

Due to the holistic analysis of properties, the tool supports in analysing and evaluating design options. However the tool does not support in identifying components with a potential for optimisation, finding suitable design options or designing potential solutions as it is only one module in an aggregate of tools. An example of different tools is given by Kleemann et al. (2016) in case of design rules or in case of multi-material design catalogues. As there is not such a catalogue, a demand can be revealed. Nevertheless an integration respectively a conjunction of different tools seems to be promising to cover the entire component development.

The elaborated system of relations results in an understanding of the relations between the determinable characteristics and the resulting component properties. However, understanding the amount of relations requires a significant effort by changing the components characteristics manually and comparing the properties to the previous properties. Consequently, an additional module is in trial phase, which enables the designer to perform sensitivity analyses and parameter studies. This may illustrate the effects of changing different characteristics within a short time. In addition a matching of properties is tested in order to compare different components e.g. regarding an equal bending stiffness. The modular structure of the software architecture allows an adaption and extension of the tool with a small amount of effort and thus the software tool may be enhanced easily.

6 CONCLUSION

We clarified the need for a methodological support in multi-material design because of an increased complexity in component development. We presented an integrated tool supporting the designer in analysing different design options which seems to be a suitable approach for facing the problems of component redevelopment. The presented tool determines concept properties such as stiffness, weight and environmental impact. For this analysis, the tool uses an abstract representation of components. This may enable the designer to fundamentally analyse different design options considering multiple criteria in an early stage of development. Thus increasing solution space especially of multi-material design may be exploited faster. Based on the preliminary results further fields of research open up. Since the presented tool is only one in a tool chain, what has to be extended is the connection to other tools taking into account further aspects of component redevelopment such as finding design options or process selection. This includes both, already existing tools and redevelopment of tools to close gaps in the tool chain. Finally, this approach is validated and enhanced in further research by the project partners.

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