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INTEGRATION OF A SYSTEMATIC MATERIAL SELECTION INTO THE DYNAMIC DEVELEOPMENT PROCESS OF VEHICLE STRUCTURE PARTS

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1. Introduction

In recent years, the automotive industry has faced increasingly tight restrictions on exhaust emissions and fuel economy. Thus, car manufacturers are presented with a delicate challenge. On the one hand, government regulations such as the US CAFE standards or the European EURO 6 laws have to be met which call for light and efficient cars. On the other hand, customer demands for performance and the integration of new systems and features also need to be satisfied, to stay competitive in the market.
The reduction of weight through lightweight design has therefore become a crucial factor to achieve these diverging goals. Next to the design itself, the selection of the right materials is key to realize weight saving potentials without compromising functional performance. This is especially true for structural vehicle components, like parts of a car body, which require a high load-bearing capacity in a limited available space.
As a consequence, the spectrum of materials used in car bodies has broadened significantly in recent years, from mainly steel parts to a mixture of steel, aluminum and fiber reinforced plastic components. Despite this increasing diversity, no systematic approach for material selection has been successfully implemented in the industry so far. Even though elaborate selection schemes exist [Ashby 2005], [Farag 2014], most manufacturers rely on experience, expert opinion and trial-and-error, when it comes to the choice of material.
The main reason for this is that most research on material selection pays little to no regard to the product development process in general and the vehicle development process in particular [Ashby 2005], [Dieter 2009]. All existing methods, such as the material indices introduced by Ashby or the matrix methods by Farag, assume perfect knowledge of the component and material requirements. Furthermore, limitations on available space are hardly considered [Pasini 2006], [Wanner 2010]. This prohibits the application of these methods for structural vehicle components which face tight size restrictions and whose requirements profile fluctuates over the development process.
Therefore, the aim of this work is to propose a new method of material selection for vehicle structure parts, which is able to consider a more realistic collocation of the material into the given design space and react to incoming requirement variations.

1.1 Structure of this paper

To generate a method for the material selection of vehicle structure parts the topics surrounding this subject have to be examined and understood. The vehicle development process and the existing methods of material selection are of particular interest, with a focus on the management of requirements. Therefore, the state of the art is presented in chapter 2 before in chapter 3 the resulting deficits will be derived. Chapter 4 introduces an approach to address these weaknesses. The following summary, as well as the additional outlook in chapter 5, complete this work.

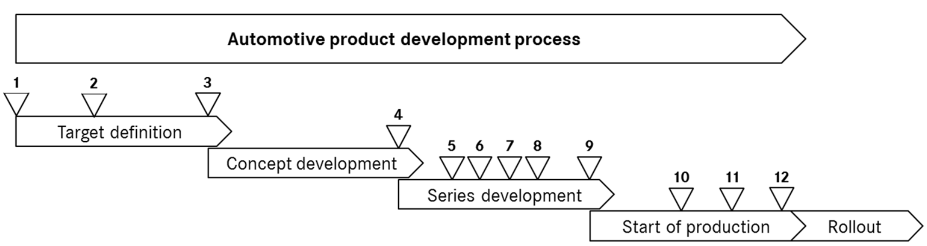
2. State of the art

2.1 Definitions of vehicle structure parts

The primary function of structure parts is the general absorption of forces and moments inside of supporting structures [Reuter 2007]. Dependent on the load carrying capacity of a component as well as the point of contact and the direction of the operating loads a sub-division into different load cases like tension, compression, bending and torsion can be made. A superposition and combination of all these load cases is possible [Friedrich 2013]. The dimensioning of structure parts mostly considers specific stiffness and strength requirements. A typical example is the stress which a car body has to withstand during driving operation. Total vehicle requirements have thereby an impact to a lot of single structure parts (cf. chapter 2.2).
The main factors influencing the determination of a material concept in such a context are the level of the loads and the available space [Ashby 2005], [Pasini 2006], [Wanner 2010].

2.2 Material selection in the vehicle development process

The vehicle development process is generally separated into pre- and series development. The transition is mostly defined by the suitability of the concept. The different process stages are organized by so-called quality gates. On these fixed milestones, the progress of the product development is evaluated and a certain level of product maturity has to be met. The nomenclature of these single stages and quality gates are manufacturer-specific. The vehicle development process is generally constructed as a project in which the standard process can be adapted and specifically detailed.
Figure 1 shows an exemplary flow of the vehicle development process. The milestones in this model are clearly defined from the start of project (1) up to the start of production (12). The suitability of the concept is verified at quality gate (4), which illustrates the transfer from the concept development to the series development. This crossover is the critical milestone for the material selection of vehicle structure parts, because at this time the functional suitability of the whole car body must be ensured [Braess 2013], [Friedrich 2013], [Schulz 2014].



1	Start of project	4	Specification sheet	7	Data model clearance	10	Pre-series
2	Product characteristics	5	Package/Design freeze	8	acquisition clearance	11	pilot run
3	Target catalog	6	First operable prototyp	9	Start-up clearance	12	Start of production

Figure 1. The vehicle development process in dependence on [Schulz 2014]

To enable this, the concept stage is further divided into sub stages, each with their own milestones. One objective of this detailed development stage is the optimal material selection for every part of the whole car body. To reach this goal, the total vehicle requirements have to be separated into appropriated system and subsystem requirements, before the translation into component requirements can be realized. In reverse order to the requirements identification, the functional validation proceeds gradually upwards which is embodied in the v-model (Figure 2) [Mayer-Bachmann 2008].

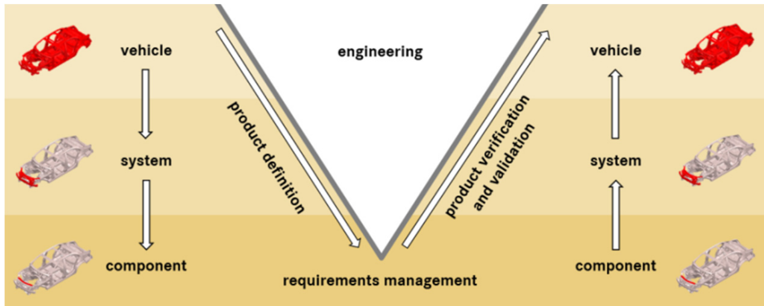


Figure 2. The v-model on the basis of the vehicle development

At the beginning of development the functional validation happens on the basis of simulations. In later stages they are supported by real experiments. The evaluation of the concepts is based on the assessment of cost, weight and functional performance. The maturity level of the car body and the precision of the structure part requirements increase with each iteration of this process [Friedrich 2013].

2.3 The material selection process

In the existing literature the material selection process is commonly divided into 4 successive steps. Thereby all the tasks of the respective components shall be clarified in stage 1 and the resulting product requirements are to be translated into the corresponding material requirements. In stage 2, on the basis of the exclusion criteria of the requirement profile, the screening of suitable materials is performed. The reduced number of material candidates is then subjected to a ranking in stage 3. For this purpose, different material parameters and -indices are used depending on the component requirements (e.g. stiffness, stability) and selection targets (e.g. minimal weight, minimal costs). Ultimately, at the top of the ranking the best qualified materials can be found which make up a short list of possible candidates.
In order to make and ensure the final decision in stage 4, additional material information of the promising materials must be obtained, to check the explicit suitability of a part by simulations and hardware tests [Ashby 2005], [Dieter 2009], [Reuter 2013], [Farag 2014], [Moeller 2014].
While there is a general consensus regarding the process sequence of the systematic material selection, there are different methodological approaches for the realization of the individual process steps in the literature.

2.4 Material selection methodology - Stage 1

As briefly described in the previous section, the focus in stage 1 is on the clarification of the task as well as the translation of the product requirements into material requirements.
Ashby focuses on the categorization of the component requirements into function, constraints, objectives and free variables. This scheme can be helpful for the classification of the requirements and is the basis for the creation of new material indices. However, the question of how the specifications for a component can be translated into material requirements is not solved [Ashby 2005].
Farag suggests the use of the “House of Quality” (HoQ) for the translation of costumer wishes into to functional requirements. The HoQ is suitable for the systematical registration of the correlation between properties and product characteristics as well as to weigh the importance of the characteristics. The material requirements do not explicitly emerge from this consideration. In addition, the functional chain from the product to the component and ultimately to the material is sometimes difficult to understand [Farag 2014].
Reuter examines the requirements management in most detail. He adopts Ashby’s categorization of requirements into function, constraints, objective and free variables and supplements this by the simultaneous allocation into goals, demands and wishes. Wishes should represent no limitation for the concept selection, but can be crucial in the evaluation. Both types of classifications can be transferred easily into each other according to Reuter. To translate the product requirements into component and material requirements Reuter recommends putting up function diagrams. The function chart visualizes how to split the functions of a system to obtain the function of its individual components. Thereby the dependencies between the individual components become comprehensible. In principle, the material,

energy and information flow are considered in a function diagram. It is questionable, if limitations on available space can be represented in a similar fashion. As a further tool of the requirement management Reuter introduces checklists and lists of questions. Such a list can help to display the basic load types, which the component is subjected to. A positive aspect is the simple application of this method. The evaluation and classification of the located requirements as well as conclusions that can be drawn from it remain open. In addition, requirements that are not covered by the limited list of questions, can lead to mistakes in the actual selection [Reuter 2013].
Similar problems also arise in the method of Dieter. He introduces a table in which relevant material parameters can be related to mechanical and thermal load cases. Similar to the list of questions, this method is rather helpful in structuring and less in the identification of requirements. Uncovered questions also leave room for mistakes. But an essential advantage is the explicit reference to characteristics which can be considered in the selection [Dieter 2009].

2.5 Material selection methodology - Stage 2 & 3

The stages 2 and 3 describe the pre and fine selection of the materials, after the requirements have been clarified in the first step. On these two sectors lies the focus of the existing literature of the material selection.
Ashby distinguishes between three basic strategies, with which out of a given requirements profile material solutions can be found. Strategy 1 describes the free search. The objective is, to find the best possible solution out of the entirety of materials, on the basis of analytical examinations. This strategy allows innovative materials solutions, but needs a detailed requirements profile. This approach is the focal point of the literature for the systematical material selection. In strategy 2 a drawn up questionnaire by experts guides the user through the selection. Thereby also unexperienced users are able to execute a selection. However, no fundamentally new solutions can be found. In strategy 3 the selection relies on collected experience and case studies. This proceeding is typically found in the industrial practice [Ashby 2003].
In order to exclude no material innovations from the outset, it should be the goal to narrow the search space of all possible materials by generating a list of promising candidates (strategy 1). Thereby a distinction is made between the steps “Screening” (Stage 2) and “Ranking” (Stage 3). In the screening stage all candidates are excluded, which are in principle unsuitable for fulfilling the designated function of the component. Here the so-called hard requirements (go or no go) are relevant, which the material must meet mandatorily, for example the applicability at certain temperatures. This type of requirements corresponds to Ashby´s category of “constraints” or the “demands” of Reuter [Ashby 2005], [Reuter 2013].
In the subsequent step 3, the performance of the remaining materials is evaluated. Thus, the most suitable candidates are identified. The performance criteria must be chosen depending on the objective. An example would be the requirement for the smallest possible component weight. In general, there are characteristics or properties by which the suitability of the material is scaled for a particular task.
For a systematic selection of materials within these stages 2 and 3 two basic methods are described in the literature. The method according to Ashby reduces a large search space to a manageable number of materials, based on the relevant material indices and displays them graphically based on material charts. The software support in the form of the “Cambridge Engineering Selector” (CES), and the direct coupling of the material indices to the material properties, makes the material selection for the users very intuitive and clear. However, the choice gets complicated to handle for more than two criteria and the number of possible material candidates is quite high as experience has shown.
The matrix method, which is described in detail by Farag, orders a limited number of materials, based on a variety of relevant and weighted parameters. The advantage over the previously proposed method of Ashby is in the consideration of any number of significant material parameters as well as the selection of a single material that meets the required properties best (explicit decision). However, this approach also includes certain disadvantages. With the large number of input parameters, the generated performance index permits no direct conclusions about certain material properties. Likewise, the application of this methodology is only practical if previously a material pre-selection was made, which reduces the number of candidates for a detailed comparison. The sequential application of the two

methods is conceivable in principle to reduce the search space and successively sort the results. The results of both methods have to be reviewed constantly.

2.6 Material selection methodology - Stage 4

For the procedure within the stage 4 there is a broad consensus of the relevant authors in literature. Simulation, experiment and the collection of accurate material data are the foci during this stage. As a result of the preceding operations a narrow range of material candidates should be present at the beginning of this phase. In this step, it is checked whether the materials actually meet the initial conditions and the final material decision is made. Instead of the pure material properties, the product properties are now in the foreground. Here, both manufacturing and the shape play a crucial role, so that the choice of materials is no longer separable from the product development process. Shape and design of a component are dependent on the material and have to consider the strengths and weaknesses of the material. Therefore, ultimately, for all relevant characteristics, such as functional performance, weight, cost and available space, the combination of shape and material must be evaluated. This information can significantly contribute to the decision-making, since many of the above characteristics are difficult to predict upfront [Ashby 2005], [Dieter 2009], [Reuter 2013], [Farag 2014], [Moeller 2014].

For this reason Farag and Reuter recommend a comparison of part concepts which utilise the different material candidates. Important aspects are weight, cost, functional performance and the reliability of the component in use. Often simulations and experiments are used to identify and examine these properties. Furthermore, detailed information of the materials is needed, which can be obtained either through material databases or directly from the manufacturer [Reuter 2013], [Farag 2014].

2.7 Material selection methodology for variable available space

For practical applications, the case of material selection for limited available space is of particular interest and extends the approaches in chapter 2.5. The packaging of systems and components is a critical factor throughout the design process and fluctuates as the overall product is developed and specified. Despite the importance of this topic, the works dealing with spacial limitations in the context of material selection are sparse.

A very simple approach can be based on Ashby's (cf. chapter 2.5) selection strategy. In the derivation of his material indices, Ashby uses a free variable, which is usually a geometric parameter such as the side length. This variable then scales, based on whichever material is used. For instance, a square beam made of steel would need a smaller side length than a beam made of aluminium, if they were to have the same bending stiffness. To accommodate this method for cases with limited available space, the maximum value of the free geometric parameter can simply be bounded. In consequence, materials without a certain minimum stiffness or strength are eliminated from the selection process.

Although this method is an easy way to include spacial limitations into the given framework of material selection, it is not without its weaknesses. Considering the load cases of bending, torsion and buckling for a set stiffness, this strategy does not lead to an optimal material distribution. To achieve a maximum of geometrical stiffness, the material should be allocated away from the load axis to the boundary of the available space (Figure 3 right).

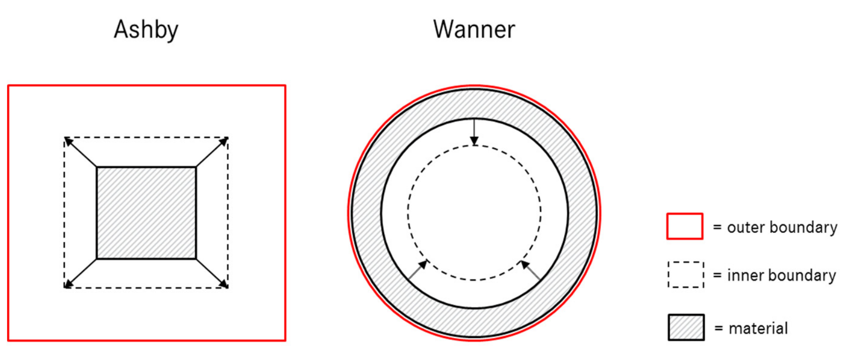


Figure 3. Different variable material selection strategies by Ashby (left) and Wanner (right)

Wanner proposed a method which accounts for these weaknesses. Considering the cases of spherical sections and sandwich panels, a new parametrization is introduced. Here, the outer boundary of the e.g. spherical cross section is fixed, while the inner one is used as a free parameter. Thus, the part basically scales inwards, in contrast to the modified method of Ashby, where the scaling is outwards (Figure 3) [Wanner 2010].

3. Deficits in the material selection of vehicle structure parts

Although several approaches for the material selection can be found in the literature, none of the processes and methods can be used holistically for vehicle structure parts. This raises the question, which extensions are essential to integrate the systematical material selection into the development process of vehicle structure parts?

The state of the art (chapter 2) reveals two major conflicts. The first one is the identification and subdivision of vehicle structure part requirements based on the total vehicle requirements. This step is complex and elaborate because of the sensitivity against incoming changes of the load or the available space. The adaptation of one part thus simultaneously changes the requirement profiles of the surrounding components. The second point concerns the translation of the identified vehicle structure part requirements into corresponding material requirements by the support of transfer functions (Figure 4).

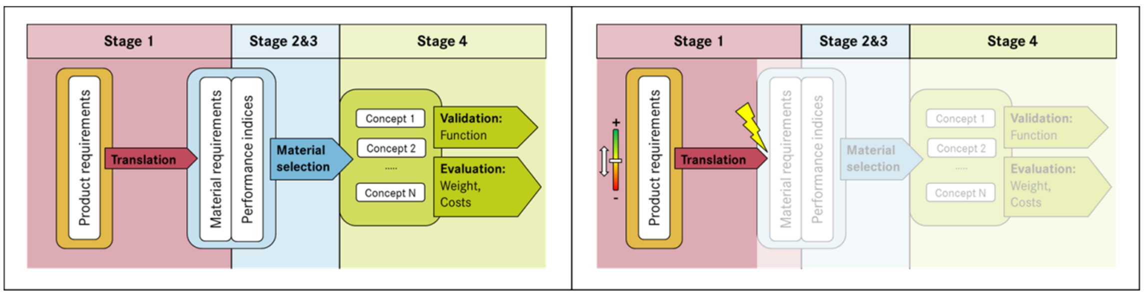


Figure 4. The previous material selection process with static requirements (left) and dynamic requirements (right)

There are existing transfer functions which account for the limitations of the available space in relation to the incoming loads (cf. chapter 2.7). However, these methods are based on cross sections which are not typically used for vehicle structure parts.

For this reason the influence of changes within the requirement profiles of vehicle structure parts are not assessable. This causes a risk for late changes of the material concept as well as a loss in the level of maturity.

4. Approach for the integration of a systematic material selection into the dynamic development process of vehicle structure parts

Figure 5 shows an extension of the existing material selection process including a dynamic requirements management (A). The loads, load paths (B) and available spaces (C) determined through the v-model need to be translated to material requirements by transfer functions (D) (Stage 1), so that the existing selection schemes (Stage 2 & 3) may be used.

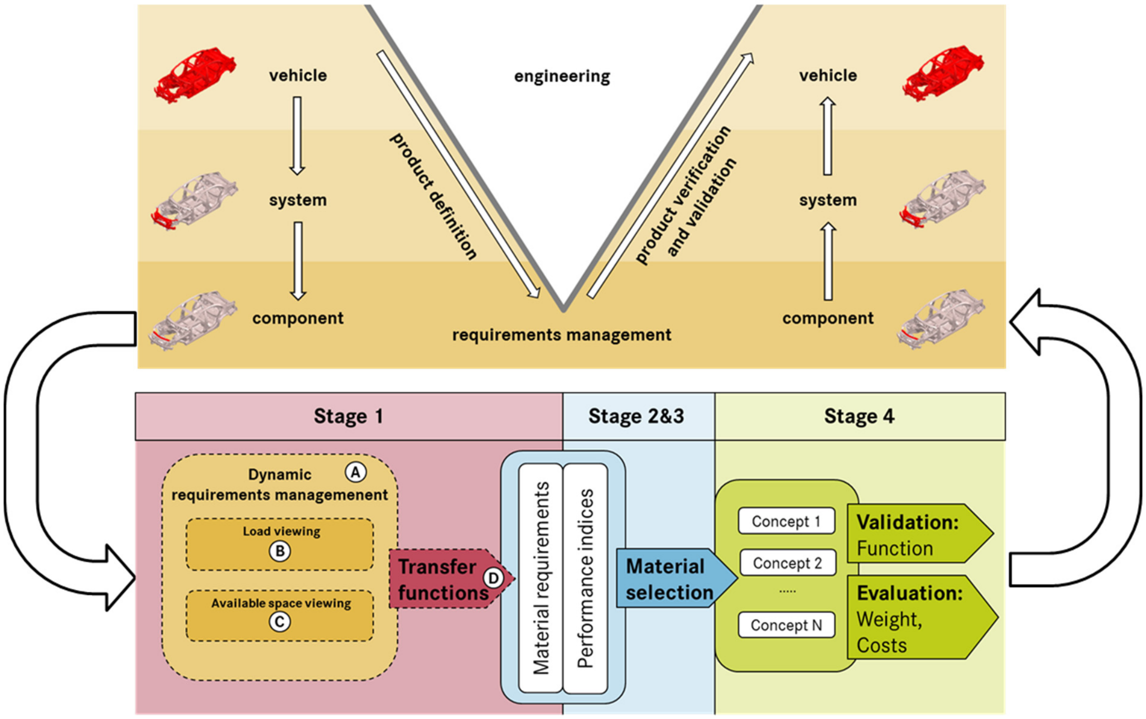


Figure 5. Approach for the integration of a systematic material selection into the dynamic development process of vehicle structure parts

The interaction between load (B) and available space requirements (C) is of particular interest as it sets boundaries to certain material parameters which have to be minded during the screening phase.
This enables an early risk assessment of the most promising material candidates where possible material or concept changes can be anticipated (Stage 2 & 3). To this end, it is helpful to create a number of probable design and development scenarios for certain parts of the car body (Stage 4). Thus, the material selection can be adapted to changes throughout the development process and the risk of a material changes can be considered when choosing the final concept.

5. Approach for the transfer functions of vehicle structure parts on the example of bending

To consider typically used cross sections in the early stage of the material selection of vehicle structure parts, a rectangular hollow profile as simplified design offers in a first approximation a more realistic illustration of the final components as the previous (c.f. chapter 2.6).
The reason therefore lays in the frequently entering load cases of vehicle structure parts like bending or torsion. In such a case an accretion of material in the outer area inside of the design space is associated with benefits of the needed quantity of material. By skilful choice for the geometrical description of the rectangle the incoming variations of the requirements could be balanced by the wall thickness t of a component. In the following step the approach shall be demonstrated on the example of a bending beam (Figure 6).

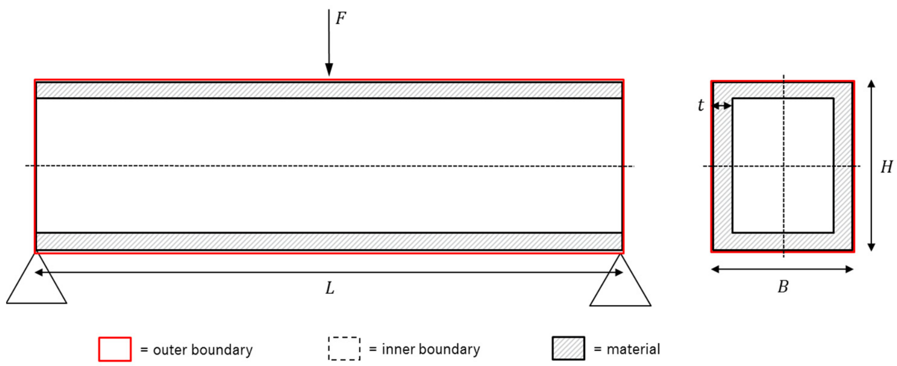


Figure 6. Geometrical description of a rectangular hollow profile for material selection

Meanwhile the height H and the breadth B define the outer boundary of the cross section. The length is described by L and the acting force by F. This parametrization results in the following formulae for the mass m and the second moment of area I in terms of the wall thickness:

$$m = (BH - (B - 2t)(H - 2t))L\rho \tag{1}$$

$$I = \frac{BH^3}{12} - \frac{(B-2t)(H-2t)^3}{12} \quad . \tag{2}$$

Furthermore, a minimum bending stiffness S_b

$$S_b \leq \frac{CEI}{L^3} \tag{3}$$

around the horizontal axis shall be given. By introducing the aspect ration $= \frac{B}{H}$, Equations (1) and (2) can be rewritten in terms of $\frac{t}{H}$:

$$m = \left(2(Q+1)\frac{t}{H} - 4\left(\frac{t}{H}\right)^2\right)H^2 L\rho \tag{4}$$

$$I = \frac{QH^4}{12}\left(\left(6+\frac{2}{Q}\right)\frac{t}{H} - \left(12+\frac{12}{Q}\right)\left(\frac{t}{H}\right)^2 + \left(8+\frac{24}{Q}\right)\left(\frac{t}{H}\right)^3 - \frac{16}{Q}\left(\frac{t}{H}\right)^4\right) \quad . \tag{5}$$

To estimate the required elastic modulus of a material for specified values of t, the Equations (3) and (5) have to be inserted into each other and afterward repositioned to

$$E(t) = E_0\left(1 - \left(1 - \frac{2}{Q}\frac{t}{H}\right)\left(1 - 2\frac{t}{H}\right)^3\right)^{-1} \quad . \tag{6}$$

A realistically range of material thicknesses have to be determined based on possible scenarios of part production and assembly (Figure 7 left). To gather this type of information, material suppliers or past production experience may serve as useful data sources. Thereby, it can easily assessed if a material would lead to a sensible wall thickness and whether it is in danger of being rendered unusable, should the load conditions or the spatial limitations become more severe.

By using the boundary condition $\frac{t}{H} = 0{,}5$ to simulate a completely filled design space, a minimum elastic modulus E_0

$$E_0 = \frac{12 S_b L^3}{CQH^4} \leq E \tag{7}$$

defines the minimum level of usable materials.
In order to sort the remaining materials by weight-saving potential, a material index has to be developed to measure their performance. However the therefore necessary elimination of t in particular in the equation of the second moment of area (5) is difficult and results in complex terms. This is a severe hindrance for the application of the method, especially for designers who are not experts in material selection. Due to this reasoning, in the next step a simplification of the formulae for the mass m (4) and the second moment of area I (5) is made by assuming thin walled sections with $\frac{t}{H} \ll 0{,}5$. This assumption is generally valid for most vehicle structure parts. Thus all terms with the order > 1 can be neglected which consequently leads to the linearized expressions for the mass

$$m_{lin} = 2H^2 L \rho (Q+1) \frac{t}{H} \tag{8}$$

and the the second moment of area

$$I_{lin} = \frac{QH^4}{12} \left(6 + \frac{2}{Q} \right) \frac{t}{H} \,. \tag{9}$$

This enables in the next step the elimination of the wall thickness t by inserting Equation (8) into (9) and afterward the separation of the material index $\frac{\rho}{E}$ (Figure 7 right) by using the stiffness Equation (3) by repositioning to the linearized mass

$$m_{lin} = \frac{12 S L^4}{C H^2} \frac{Q+1}{3Q+1} \left(\frac{\rho}{E} \right) . \tag{10}$$

Thereby the visualization of the concept comparison in the classical material selection diagrams (Figure 7) as well as the integration of this methodical approach into the CES Selector is feasible.

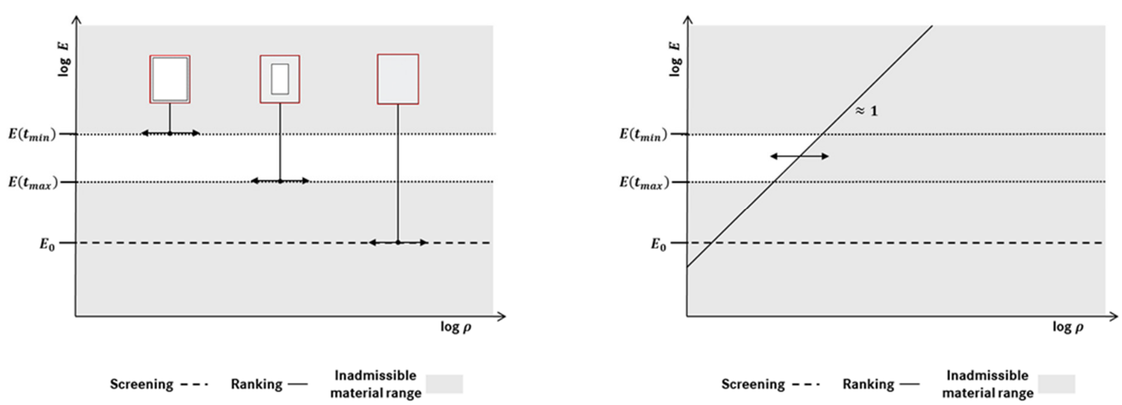


Figure 7. Material screening (left) and ranking (right) in the typical selection diagrams

Possible changes of the entering load (F) or the available space (B, H, L) have a direct effect on the selection range of possible materials as well as the wall thickness (t) of the concept. By early variations of the input quantities the reliability of material concepts is assessable.

6. Conclusion and outlook

The current difficulties concerning the integration of existing material selection schemes into the development process for vehicle structure parts have been examined and presented. The fluctuation of load requirements and available space has been identified as a crucial conflict point, since these two factors have major implications on the choice of suitable materials. As a consequence, the overall functional performance of the structural vehicle parts cannot be guaranteed and is highly insecure.

To solve this problem, an approach has been developed that couples the v-model with the requirements management of the material selection (cf. chapter 4). This allows the depiction of and adaptation to dynamic changes over the course of the development process by translating these component requirements to material requirements with the use of a newly developed transfer function (cf. chapter 5). Through the simulation of possible scenarios and the resulting changes in loads and available space the suitability and risk of promising material concepts can be evaluated.

For a further extension of the applicability the distribution of entering changes within the loads or available spaces should be presentable in detail for every single component. Additionally the developed approach for the transfer function in consideration of bending (cf. chapter 5) must be extended for some further typical load cases of the car body like compression (buckling) or torsion.

On the basis of these add-ons corresponding concepts in consideration of the component costs and the producibility can be finally executed in a case study to validate this kind of approach.

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