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ROBUST CONCEPTION OF VEHICLES CONSIDERING REGION-SPECIFIC REQUIREMENTS

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ABSTRACT

Changes in automotive markets and technologies amplify the issue of fulfilling requirements for all customers within a single vehicle concept. An increasing development of regional markets demands vehicle concepts, which fit the customer's wishes and satisfy the environmental conditions.
In this paper, a requirement-driven approach is proposed. The approach introduced deals with the issue of relations between the customer's requirements and the technical characteristics and properties, especially in the early stages of product design. Here, the vehicle requirements are determined and related to the vehicle environment. And together with experts in each vehicle field the relationships between components, among requirements, and between components and requirements are traced and analyzed. With this approach, vehicle concepts can be compared based on the level of satisfaction that their different selected components achieved in specific markets.
The analysis is achieved by modeling all these relationships in the Systems Modeling Language (SysML), which is common practice in system and software engineering where multiple systems need to be described

Keywords: vehicle concept, requirements, robust design, conflicts analysis, knowledge management

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1 INTRODUCTION

To achieve consumers' satisfaction in different regions, differences between customers and their specific environment have to be traced. These differences generally result in several sets of requirements. These sets of requirements have as well impacts on the vehicle's technical characteristics and properties. To find one vehicle concept, these impacts have to be considered in the beginning of the design process.

To illustrate the development of region-specific vehicles, this paper starts with defining factors, which describe the surroundings of the vehicle (environment), like the climate in a region or different cultural circumstances, (Wallentowitz et al., 2009). Because this step has been rarely supported with methods so far, some influencing factors from the environment aren't considered in the vehicle development. Therefore, this research aims to determine the influencing factors from the vehicle's environment systematically and to ascertain their effect on a vehicle. To do so, a software application helps to document these factors and to illustrate the influence of the vehicle's environment on its technical characteristics and properties. The documentation of the vehicle's environment in a supporting application allows the analysis of these information for different customers to determine specific sets of requirements as shown in Figure 1.

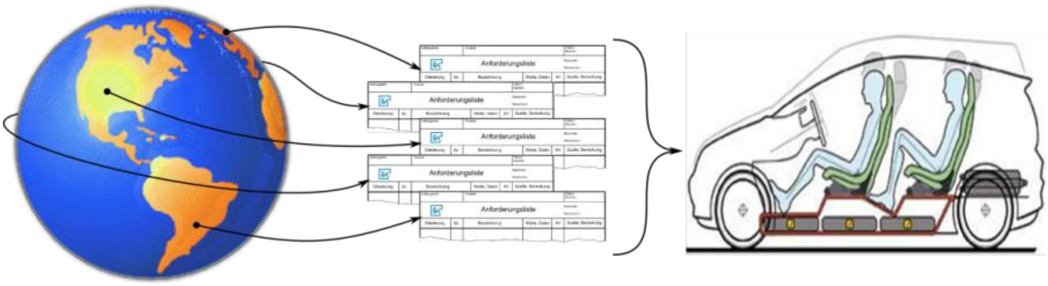


Figure 1. Changes on vehicle characteristics resulting from sets of requirements, which are based on different customer needs and environment influences

During the information acquisition for different customers and specific environments, first conflicts between requirements can already be identified (e.g. top requirements for main customers are "high performance" and simultaneously "low fuel consumption"). These conflicting requirements should be taken into account during the vehicle concept design (Nehuis et al., 2012). In addition to this, economies of scale prevent the development of unlimited numbers of vehicle derivatives, which would be a solution to adapt the vehicle to different sets of requirements. Thus conflicts between technical design and vehicle feasibility occur (Prinz et al., 2012).

Requirements depending on vehicle properties (e.g. vehicle total weight or selling price) cannot directly be fixed because they result from the interaction between numerous characteristics. Though, it is not always clear which characteristics satisfy the customer needs at best because the interactions are extremely complex (Stechert, 2010). In addition, the definition of design parameters and product characteristic as well as the selections of vehicle technologies are responsibilities distributed across different departments in a company. While each department has its own view on the system, only a few persons keep the overview about the interaction between all these systems. These persons, however, do not have the knowledge about all details. So, how to distribute a holistic view to all development departments and designers? And how to make use of the interactions between these systems to select the vehicle concept and components that best fulfill the requirements from given customers and vehicle environments?

The Institute for Engineering Design from Technische Universität Braunschweig (IK) proposes a requirement driven approach for the development of complex products, this by modeling systems, objects and their dependencies in an object-oriented modeling environment. In a first step a model is presented which contains the product environment and describes the influence on the product's technical side. This paper illustrates its approach using the example of a vehicle concept.

2 STATE OF THE ART

2.1 Determination of requirements in the design process

To develop a successful product, it is important to fulfill customer's needs. Thus, requirements for the overall system or its subsystems have to be determined carefully in the beginning of the design process. This step is also highlighted in established design methodologies like in "Product Design and Development" from Ulrich and Eppinger (Ulrich, 2011). For the determination of requirements, the Association of German Engineers defines "clarifying and specifying the task" as the start point (VDI, 1993). This step starts with product demand description and definition of boundary conditions. As a result a list of requirements is created. Together with the determined values and data about customer and the environment, this list constitutes the so-called set of requirements and represents a first product's model.

In the further course, it may happen that already determined requirements have to be changed in the design process. This situation occurs for example if it is only possible to fulfill a requirement by using additional knowledge which is gained in this process, or if boundary conditions and restrictions appear during the process (Stechert, 2010). This usually results in increases on cost and time pressure at later steps of the design process. Particularly, requirements that have been defined in the conceptual phase can only be modified with high effort, see Figure 2.

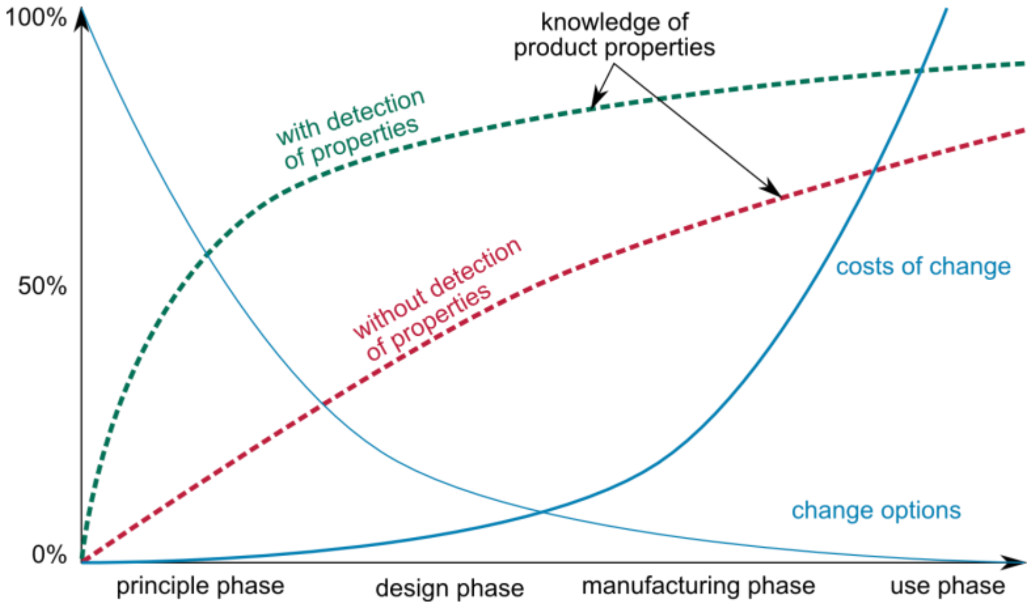


Figure 2. Reducing modification input and costs by early recognition of the system properties, regarding (Ehrlenspiel, 2009)

To reduce development costs, major product changes, especially in later steps of the design process, should be prevented. In order to avoid these costs, several methods and tools are used, e.g. raising the level of knowledge in early steps of the design process (Ehrlenspiel, 2009). There the knowledge is already needed to carefully determine the product's requirements. For this, basic information about the product and its environment should be known. In any case it is advisable to spend enough time in determining requirements in an early step of the design process. Eventhouth this will take more time, an intensive task clarification normally causes reduced development time and costs in total.

2.2 Embedding a product into system context

In order to determine requirements as comprehensive as possible in an early step of the design process, the customer needs and the product environment have to be analyzed extensively. But an entire overview about all influencing factors on the product is difficult to achieve, because a large number of factors are related to the product in real life (Nehuis et al., 2011). Besides, designers need to have an understanding of the individual relations within products and influencing factors. This understanding helps designers to see the consequences that a single requirement has on the product or its subsystems.

Furthermore, it allows them to define requirements carefully. Without system knowledge, designers may determine requirements which are partially or not feasible.
Boundary conditions that restrict the design of the product could be environmental factors like climate conditions, or customer needs like luggage capacity. Humidity, for example, will have in some climatic regions significant effects on a technical product; this has to be determined and considered in the requirement list. If there is high humidity, it is necessary to ensure adequate and viable corrosion protection.
Several approaches try to integrate requirements management into a holistic product design methodology (cp. (Albers and Meboldt, 2007) (Andreasen and Hein, 1987) (Kickermann, 1995) (Pahng et al., 1997) and (Weber, 2005)). In a previous in-house article called "Requirements Management from an Interdisciplinary Point of View" more than 60 design processes from mechanical, electronics, software and systems engineering were analyzed with focus on requirements (Stechert et al., 2011). The article shows that modeling complexity for requirements and their relations need further investigation.
As mention before, Requirements have an impact on product characteristics and properties. In a holistic approach, this results in a chain reaction that must be considered during the product development; especially for complex products. The relations between environmental factors, technical requirements, characteristics and parameters of a vehicle are illustrated in Figure 3.

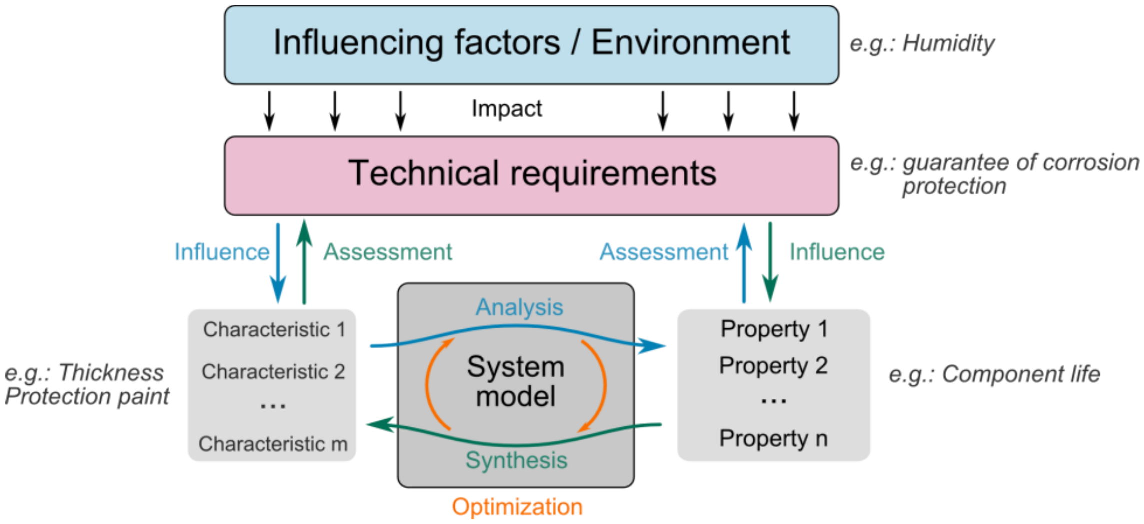


Figure 3. Schematic illustration of the relation between influencing environmental factors, technical requirements, characteristics and properties of a vehicle concept

Usually, a requirement doesn't have an influence on only one characteristic or property, but on several at the same time. Thus, conflicts can occur during the implementation of the set of requirements. In addition, a characteristic or a property is generally determined by more than one requirement. For example, technical requirements like guaranteeing corrosion protection and reduction total weight lead to such a conflict: The first requirement increases the thickness of the protective lacquer. But at the same time the total weight of the product also increases (Weber, 2008).

2.3 Technical requirements and embedding the product in its environment

When considering the product environment and in particular the vehicle environment during the product life cycle, many influencing factors can be detected. These include obvious ones, like e.g. infrastructure or legislation, but also such as individuality of the owners or different cultures (Wallentowitz et al., 2009).
Already in the 1970s, methodology started with investigations of the product environment. Some approaches pursued the goal to support the determination of requirements. General checklists (Pahl, 1975) or morphological search procedures (Franke, 1975) were one of the first supporting tools. In order to facilitate a target-oriented, product-related clarification, these methods evolved in to computer aided tools, with a branch-specific level of detail (Kickermann, 1995). These propositions did not find a wide range of practical use, but adaptable software applications can probably change this. These

tools have to be more user-friendly and need to be expanded with specific product knowledge (Franke et al., 2011).

Aiming to improve the existing applications, this research traced the influencing factors and technical requirements in a relation system, where influences and effects were illustrated by connections. To make these factors accessible, the relation system is documented in System Modeling Language (SysML). SysML is based on the Unified Modeling Language (UML), a programming language for modeling complex systems (OMG SysML, 2012). For this, the SysML-Editor called Artisan Studio is used. The editor enables to document and graphically illustrate influencing factors, requirements and their connections. In addition, each element can be associated with additional information, (Stechert and Franke, 2009a). The empirically data is time-dependent and reflects the current status in a region. In contrast the technical requirements, the influencing factors and the relations are timeless and can be generally used (Weilkiens, 2006).

Due to the systematic analysis of the vehicle's environment and to the documentation of the system relations in SysML, the basis for a conscious determination of requirements is given. With the connection and the specific information of each element, the influence of the environment on the vehicle is described. In order to show the designer the information to determine the requirements, a supporting tool helps to select and show the sections of the model with the needed knowledge. This is illustrated in Figure 4.

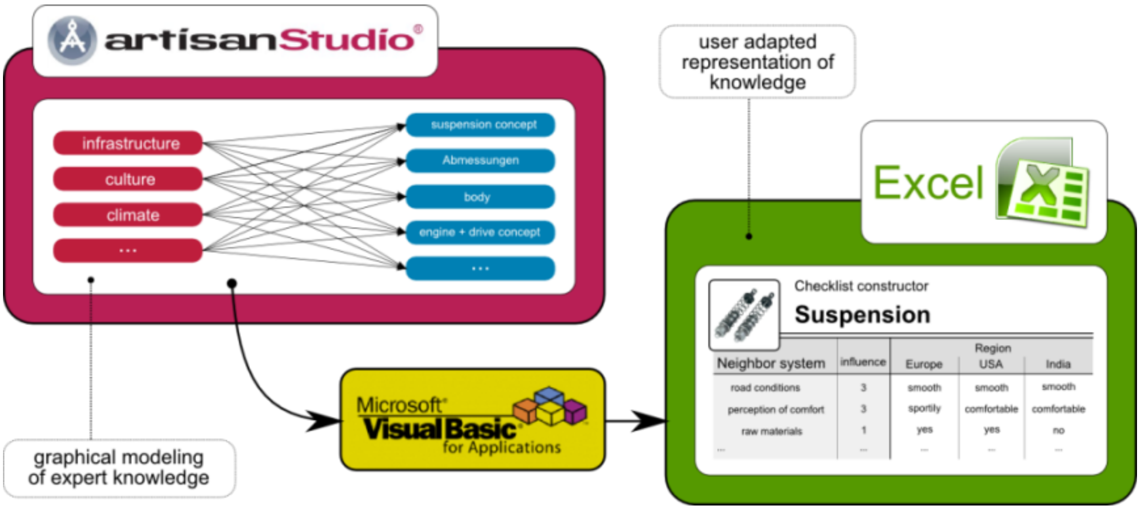


Figure 4. Scheme of knowledge compilation adapted to user expertise

The user-centered output of information makes the determination of technical requirements easier; and these results can incorporate different environments and scenarios. With the user adapted representation of the knowledge spreads, requirements can be easily acknowledged.

3 CONFLICTS IN DESIGNING A VEHICLE

During the development of a vehicle, a huge number of conflicts related to the vehicle design appear (Ponn, 2011). Referring to (Fischer, 2004), these conflicts occur when multiple optimization is sought, e.g. if one requirement can't be fulfilled without degrading another requirement. In this context, it is difficult for the designer to survey the entire network of characteristics, properties and requirements to achieve the correct trade-off. Therefore conflicts in vehicle design should be supported with computer-aided applications.

3.1 Conflicts between the vehicle and the vehicle environment

Region-specific requirements, like different customer wishes, legislation or varying environmental factors are partially considered during the vehicle development (Wallentowitz et al., 2009). Increasing customers' wishes for individual mobility, as given in BRIC countries, make it more and more important to include requirements for vehicle on the different regions. One comprehensible example is the climate: The average daytime temperatures in Rockhampton, Queensland in Australia, from January to December are between 16,2°C and 26,7°C, whereas the temperatures in Werchojansk, Russia, vary between -47,0°C and 15,2°C (source: German Weather Service). Besides this simple

example concerning different climatic conditions, less trivial factors, like cultural differences, have also an influence on the vehicle. As a result, different requirements (e.g. focus region 1 “high longitudinal acceleration”, focus region 2 “low consumption”) can be requested and should be taken into account during the conceptual design phase (Braess and Seiffert, 2007).
A computer-aided model containing the vehicle’s environment, as it is described in section 2.3, demonstrates the relation between different environmental factors and the vehicle concept. Next to the relation between environmental factor and vehicle, more information can be added. When a property, like e.g. “vehicle width and height” has to be defined by the designer during the conceptual phase, all influencing factors and their effects on this property can be displayed by the tool. Further region-specific information is also provided. Figure 5 shows the analysis of the knowledge model with the tool schematically.

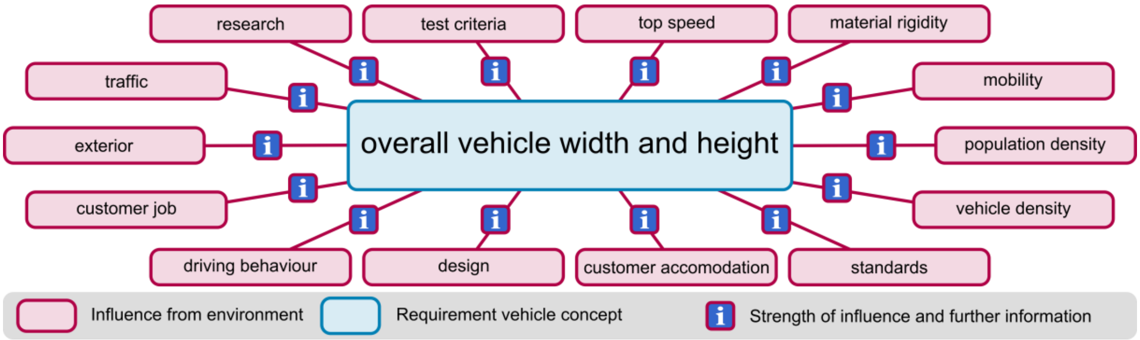


Figure 5. Schematic representation of environmental influencing factors which affect the cross-sectional area

The overall vehicle width and height get influenced by several different factors, as shown in Figure 5. One example is e.g. the top speed that is related to the vehicle’s cross-sectional area by the drag equation:

$$F_D = 0{,}5 \cdot \rho \cdot v^2 \cdot c_D \cdot A \tag{1}$$

Drag force is defined as F_D, mass density of fluid as ρ (and $\rho_{air} \approx 1.2$ kg/m³), vehicle velocity v is relative to the fluid, drag coefficient is c_D and reference area is A (in this case: cross-sectional area). A significant parameter of a vehicle is e.g. the product of drag coefficient and cross-sectional area $c_D \cdot A$. Three examples with varying values are: the Volkswagen Caddy Life ($c_D \cdot A$ = 0,99, max. speed v_{max} = 170km/h), Volkswagen Golf VI 1.6 TDI Bluemotion ($c_D \cdot A$ = 0,69, v_{max} = 189km/h) and Volkswagen Polo V 1.6 TDI ($c_D \cdot A$ = 0,66, v_{max} = 180km/h). With their varying values these models fulfill different requirements. But not only the top speed has an influence on the design of the cross-sectional area, also the shape is of importance. A large cross-sectional area often appears in a transporter, where as a small cross-sectional area leads to the impression of a sports car.
As a third example for influencing factors on the cross-sectional area, customer accommodation is highlighted in terms of a good view through the windscreen. Small cross-sectional area induces to smaller windscreen and thus a smaller field of vision. These influencing factors illustrate that it is generally not possible to realize a large fields of vision and a sportive design simultaneously. And larger values of $c_D \cdot A$ imply higher fuel consumption; what leads to a conflict in the requirements because the minimization of the fuel consumption is one of the most important aims during the vehicle development.

3.2 Conflicts in the vehicle concept itself

The vehicle is composed of components, and a right component combination will satisfy the sets of requirements (e.g. the vehicle fuel will be defined by the engine type). In the last section it was also mentioned that requirements are also influenced by other requirements. The relations among requirements themselves, components themselves and between requirement and components need to be considered to help vehicle designers to make the right decisions e.g. when choosing the components for new electrical vehicle concepts. To cope with this interrelationship complexity, IK has done an additional adaption to the SysML extension (Stechert et al., 2010a).

By modeling the requirements into a SysML diagram, the impact that requirements have on each other can be defined. An analysis of these collected influences can identify missing objects and the model can be completed, see also (Chahadi and Birkhofer, 2008). In addition, the analysis identifies inconsistencies and goal-conflicts in the model.
In the SysML, the requirement support modeled as a <<trace>> relationships (Stechert and Franke, 2009b). Support is a key intra-model relation for a target-conflict. Support can be positive, negative or exclusionary. To illustrate this, figure 6 shows and example where three properties are modeled in SysML as rectangular objects. Here the designer defines that optimizing the cross-sectional area will have a positive effect on the optimization of the specific air resistance, but because the aerodynamic can be optimized by other means aside from the cross-sectional area (e.g. better drag coefficient due to less turbulences), this last influence is not that strong and can be considered as a positive unidirectional support or <<trace>>. The market experts will say that an optimization of the cross-sectional area negatively supports the cabin volume and this conflict applies in both directions. By analyzing these two relations a third relation can be found that was probably not clear to all players.

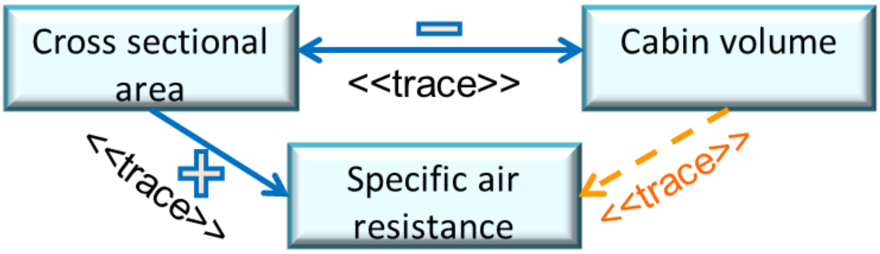


Figure 6. Definition of requirements and interrelations in SysML

Based on earlier work on requirements tools developed at IK, a semi-automatic goal-conflict identification has been realized (Franke et al., 2010) (Stechert et al., 2010b). A macro identifies none externalized relations on the basis of the existing relations. The interpretation of whether this is a support, a conflict or there is indeed no-relations cannot be made automatically. Nevertheless the matrix assists in identifying those locations where it is useful to review the complex model. All requirements from all expert areas are put into the same model and the conflict analysis goes across all these areas. In this way, new conflicts are found in areas where experts do not usually work together.

4 FINDING A ROBUST CONCEPT FOR THE VEHICLE

Once the requirements for a vehicle concept are defined, their interaction can be modeled in a relationship system. Because the relations are modeled and the requirements are revised within the system, the influence of each requirement (i) is measurable. A new developed application adds the number of positive supports of a requirement multiply by a factor a, and the number of not affected requirements. Factor a is defined by the project experts. Here it is considered that no support is better than a negative support since it allows the optimization of the complete concept without negative effects elsewhere.
During the modeling process, requirements are labeled by priority (p): “must have” (p = 0), “highly desired” ($p = 10$), “desired” ($p = 7$) and “nice to have” ($p = 3$). “Must have” requirements are requirements that all vehicle concepts need to fulfill. If a concept doesn’t fulfill requirements with priority “must have”, it doesn’t achieve the selection phase. All other requirements will be weighted by the product of i times p as shown in Equation 2. The requirement weight or w supports the decision making process when trade-offs need to be made.

$$w = i \cdot p \tag{2}$$

A vehicle concept aims to fulfill the requirements through its characteristics and properties. Some of these requirements can only be fulfilled by the complete vehicle. Other requirements can be allocated to single components or component systems. On this basis, the component systems and the single components are defined and brought into the model. Single systems (chassis, electrical, body…) and the total vehicle are also put into the model to allocate the matching requirements. Figure 8 displays this relations and modeling process. In this example, based on the fuel availability and quality, the requirement *fuel* was allocated to a system component called *engine*, so the <<allocation>> relationship was modeled (upper arrow).

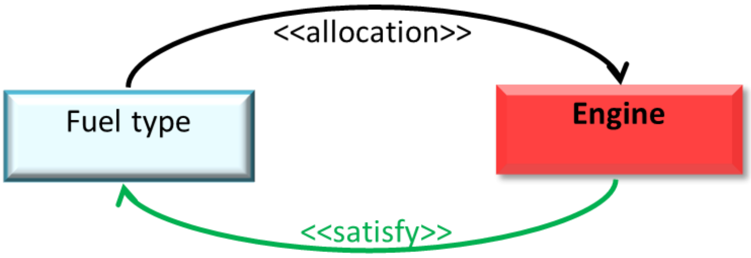
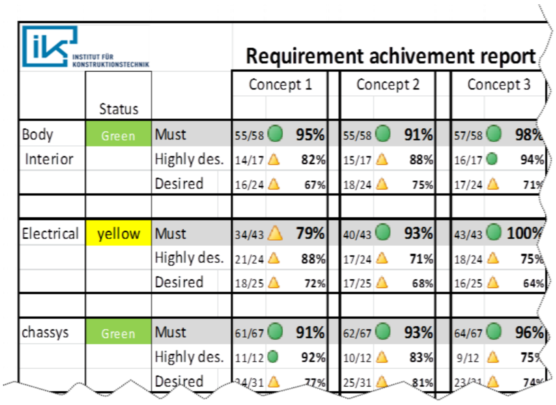


Figure 8. Component definitions (right) based on allocation from requirement (left)

Single components are added to the modeled system components and these are submitted to the total vehicle system. The resulting structure and the dependencies facilitate the system understanding for all experts working on the model and help in selecting vehicle components for the vehicle concepts.

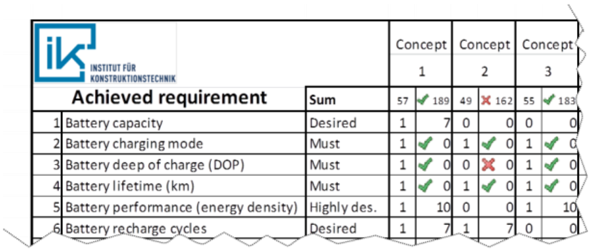
The designer can now use the model, which is built in SysML, to create a diagram of his vehicle concept. Thus a tool supports the designers to keep the holistic view and understanding on a complex model during the conception of a vehicle. The tool is not created to generate the concept itself. Beside the requirement weight assessment, this tool offers the possibility to see the influence of the component on their requirements.

Once the expert recognizes that the component's properties satisfy the requirement traced to it, he places a <<satisfy>> relationship in the diagram. This closes a circle as shown in figure 8 (lower arrow). The analysis tool detects these closed circles. With this data it creates 2 reports, the first one (figure 9, left) shows the number of requirements already satisfied versus open, this divided by system departments and segmented by requirement priorities. This helps the designer as well as the department teams to get an overview about the process status. The second report (figure 9, right) comes in place once all "must have" requirements have been satisfied, ranking the concepts against each other. The vehicle concept ranking (r) is the sum of the requirement weights (w) that the vehicle concept has satisfied. Herewith, the developers have the possibility to compare the different vehicle concepts based on the requirement satisfaction. The satisfaction of the requirements is not only illustrated in terms of quantity of requirements been satisfied, but also which influence the requirements have on the vehicle concept. (Sánchez Ruelas et al., 2012).



Requirement achivement report

	Status		Concept 1		Concept 2		Concept 3	
Body Interior	Green	Must	55/58	95%	55/58	91%	57/58	98%
		Highly des.	14/17	82%	15/17	88%	16/17	94%
		Desired	16/24	67%	18/24	75%	17/24	71%
Electrical	yellow	Must	34/43	79%	40/43	93%	43/43	100%
		Highly des.	21/24	88%	17/24	71%	18/24	75%
		Desired	18/25	72%	17/25	68%	16/25	64%
chassys	Green	Must	61/67	91%	62/67	93%	64/67	96%
		Highly des.	11/12	92%	10/12	83%	9/12	75%
		Desired	24/31	77%	25/31	81%	23/31	74%



	Achieved requirement	Sum	Concept 1		Concept 2		Concept 3	
			57	✔ 189	49	✘ 162	55	✔ 183
1	Battery capacity	Desired	1	7	0	0	0	0
2	Battery charging mode	Must	1	✔ 0	1	✔ 0	1	✔ 0
3	Battery deep of charge (DOP)	Must	1	✔ 0	0	✘ 0	1	✔ 0
4	Battery lifetime (km)	Must	1	✔ 0	1	✔ 0	1	✔ 0
5	Battery performance (energy density)	Highly des.	1	10	0	0	1	10
6	Battery recharge cycles	Desired	1	7	1	7	0	0

Figure 9. Requirement achievement report (left) and vehicle ranking based on requirement achievement (right)

Optimization loops have to be done like in every design process, however due to the transparency of the system, it is expected to reduce the number of loops.

5 CONCLUSION

Because of the increasing globalization new target markets are arising in the automobile industry. Therefore also regional-specific requirements must be considered in the vehicle development process. In order to handle these requirements and to limit the rising development time and cost simultaneously, the designer has to be supported by specific methods and auxiliary tools already in the early step of product development.

The Institute for Engineering Design from Technische Universität Braunschweig has proposed, based on previous System Modeling Language – SysML – applications, an assessment tool, which supports during the selection and development of vehicle concepts and components. In a first step a model can be used which contains the product environment and describes the influence on a technical product. Thus the model helps the designer to specify and clarify the task. If principle solutions of the product already exist, the success of the product in different scenarios can be evaluated afterwards. Based on the model the tool is able to evaluate the performance-influencing factors systematically from the given environment and to highlight their effects on the technical components and its properties of the vehicle.

Due to the fact that the tool allows the tracing of relationship among the vehicle environment, the requirements and the vehicle components, additional reports can be created to find missing and/or conflicting requirement-requirement influences.

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