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PRIORITIZATION OF VALIDATION ACTIVITIES IN PRODUCT DEVELOPMENT PROCESSES

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1. Introduction

Product development deals with an area of conflict between customer satisfaction, efficient product development concerning development time and costs and competitive pressure. In today's complex mechatronic product development processes more and more functions, requirements and interdependencies are included and more and more disciplines are part of the process. Considering the innovation pressure regarding new products, designers tend to include highly integrated and interdepending parts to fulfill functions required by the customers. Additionally the designers have to meet high requirements concerning safety and robustness with simultaneously shorter development phases and high cost pressure very often. Especially major iterations in the late development process lead to high costs due to increasing rework effort [Weber 2009]. So these late iterations have to be avoided with a minimum of effort. Especially in early phases of the development processes uncertainty is all-dominant – but particularly in these phases the influence on the costs is very high [Ehrlenspiel 2009].

Therefore validation is a major activity and has to be included into the development process also and in particular in early phases by integrating simulation approaches as it is shown in the IPEK X-in-the-Loop-Framework (cf. [Albers and Düser 2010]). At the same time building up complex component models and executing system tests typically lead to longer development phases. Hence only by validating the right things and by validating in the right way the process is under control and the goals can be reached. The XiL-Framework supports the designers in defining how to validate but methodological support is needed to determine what to validate and thereby to prioritize the validation activities.

This is the basis for the approach presented in this paper with the goal to support the designers in estimating an efficient proportion between low development time and cost on the one side and sureness about the development of the right product on the other side which can be assured by validation activities.

In the next section iterations in product development processes are described and different characteristics of iterations are presented. Section 3 describes the role of validation activities in product development processes and the IPEK XiL-Framework. In section 4 the approach for prioritization of validation activities is presented which bases on the determination of the most critical sub-systems. In the following section 5 this approach is clarified by applying to battery system design. The last two sections close with a discussion and a conclusion and outlook.

2. Iterations in product development processes

Change and iterations are ubiquitous in today's product development. They are a result of wrong assumptions and/or wrong decisions and therefore always require an adjustment. These changes can lead to iterations. In engineering design practice, unforeseen major iterations usually lead to pressure

of time resulting in several escalation strategies with the overall objective to save the market launch date (cf. [Meboldt et al. 2012]). But not every change directly leads to major iterations. At this point it is necessary to differentiate between different kinds of changes.
For Jarratt et al. “an engineering change is an alteration made to parts, drawings or software that have already been released during the design process. The change can be of any size or type, can involve any number of people and can take any length of time“ [Jarratt et al. 2003] acc. to Jarratt et al. [2005]. This is due to the fact, that an engineering change e.g. of a single component can affect other elements of the system like objectives or other components and possibly decrease their degree of fulfilment. So the propagation of a single change through the rest of the system is an important factor concerning resulting major iterations.
Eckert et al. divides engineering change in two different types, ending change propagation and unending change propagation:

- “Ending change propagation – consists of ripples of change, a small and quickly decreasing volume of changes, and blossoms, a high number of changes that are nonetheless brought to a conclusion within the expected timeframe.
- Unending change propagation – characteristic of this type are avalanches of change, which occur when a major change initiates several other major changes and all of these cannot be brought to a satisfactory conclusion by a given point” [Eckert et al. 2004] acc. to Jarratt et al. [2005] (see Figure 1).

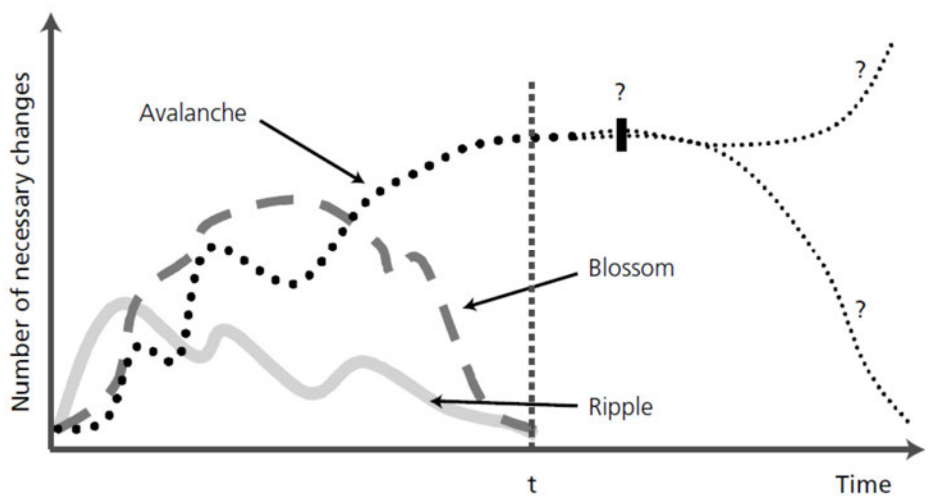

Figure 1. Types of change propagation [Eckert et al. 2004] acc. to Jarratt et al. [2005]

Considering that, especially the avalanches of change have to be avoided primarily due to the resulting major iterations which lead to high costs especially in late development phases.
To avoid avalanches of change also is the purpose of the approach of Albers et al. who prioritize the development activities in dependence of the impact of single objectives and their current degree of maturity (see Figure 2). In this case the degree of maturity is defined as the completeness of understanding and realization of an objective whilst the impact is described as the consequences of an event or decision in terms of necessarily resulting effort/cost/time for the respective system [Albers et al. 2011]. The impact can be understood comparably to the three different types of change propagation. E.g. a high impact means unending change propagation in terms of avalanches.
Elements with low degree of maturity are characterized by a high degree of uncertainty, which means the risk of a later change is high due to missing knowledge about the interdependencies. Thus Albers et al. point out the elements with a high impact as major development tasks with the goal of reducing the uncertainty (see Figure 2) [Albers et al. 2011]. This again reduces the risk of a later change.
In this major development tasks the activity of validation is of high importance, since the validation activity generates new insights and understandings about an element (e.g. components). This increases the degree of maturity and reduces the risk of unforeseeable late changes.

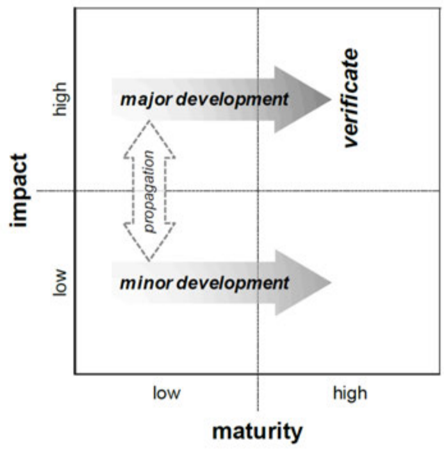

Figure 2. Maturity-Impact-Matrix [Albers et al. 2011]

Therefore the activity of validation as the central activity of product development processes is described more in detail in the following section.

3. Validation in product development processes

"Validation is the continuous and systematic comparison of the accomplished objectives of the current situation with the planned state" [Albers 2010] and an appropriate adjustment. Only after validation, an object can be considered assured to meet the objectives and uncertainty can be reduced. For Albers, validation is the central activity in product engineering since only in validation, knowledge evolves, which causes deeper understanding about the systems behaviour [Albers 2010]. This deeper understanding reduces uncertainty. To reduce the risk of a late change associated with major iterations validation should be part of the process from the beginning on to shift the necessary changes and adjustments to early phases (frontloading cf. [Weber 2009]). This is only possible by using simulation approaches. Thus virtual and physical validation methods have to be considered in an integrated manner. Therefore IPEK – Institute of Product Engineering developed the "X-in-the-Loop-Framework" which consequently integrates virtual and physical modelling respectively simulation and test [Düser 2010], [Albers et al. 2013].

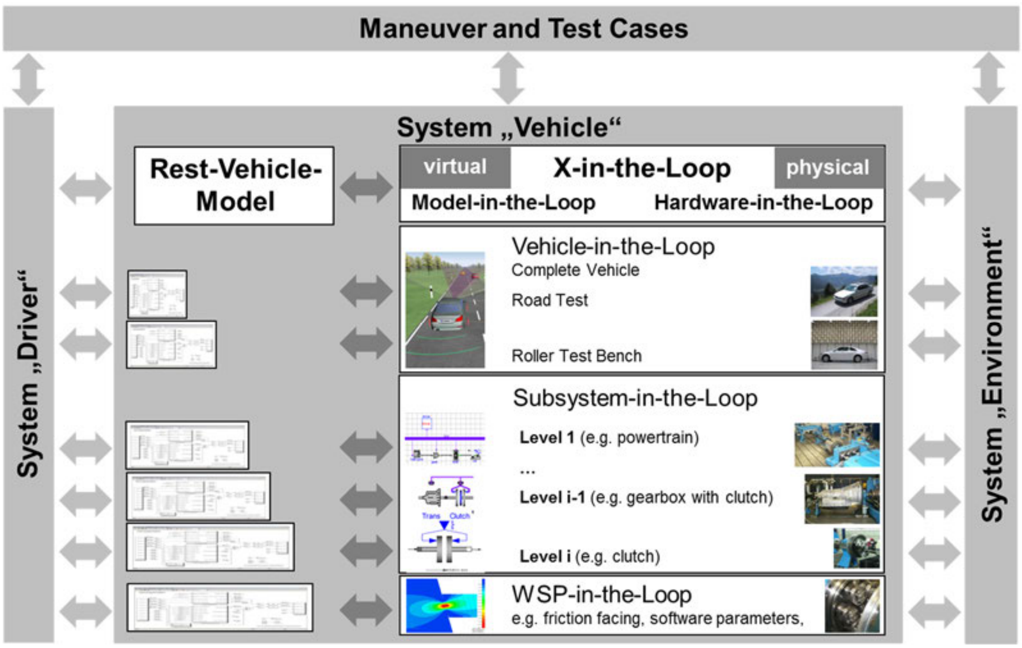

Figure 3. XiL-Framework (cf. [Albers and Düser 2010])

The XiL-Framework represents a holistic and integrated development and validation Framework for mechatronic systems existing of different layers (element-in-the-loop-layer, the subsystem-, the system and the vehicle-in-the-loop-layer) in which the System under Development (SUD) can be a physical or a virtual model or prototype. To be able to have loads which are comparable to the reality on each layer the rest vehicle is simulated and always connected to the driver and the environment [Albers and Düser 2010]. The SUD is validated under terms of special test cases and maneuvers.
The Framework describes all the possibilities of validating a special system with all relevant influences which have to be considered – virtual or physical. Therefore it supports the definition of validation environments and the connection between physical and virtual subsystems. But it does not actively support the designers to decide which combination between physical and virtual systems is the most feasible one nor in deciding which components to be validated with which priority and in which development phase. Therefore a method for prioritization of validation activities is necessary which it described in the next section.

4. Approach for prioritization of validation activities

As described in section 2, major development tasks are related to elements with high impact and low degree of maturity respectively high uncertainty (see Figure 2). In section 3 validation is described as the central activity to reduce this uncertainty. Hence elements related to major development tasks have to be validated with highest priority. Thus, to be able to find the major validation activities a method to rate the two dimensions impact and degree of maturity for every element has to be developed.
The degree of maturity stands for the understanding of an element and can therefore be described as the uncertainty about the "successful operation" of an element. To be able to rate this dimension it has to be divided into more detailed aspects. On the basis of an empirical investigation about chances and risks in dependence of the degree of novelty Koppelmann describes two criteria which influence the probability of success of a diversification strategy respectively a new product on the market – the perspective "technology" and the perspective "market" [Koppelmann 1997]. Hence, this probability is dependant from the level of familiarity of the used technology and of the market. This match very well to the degree of maturity since both describes the uncertainty about reliability.

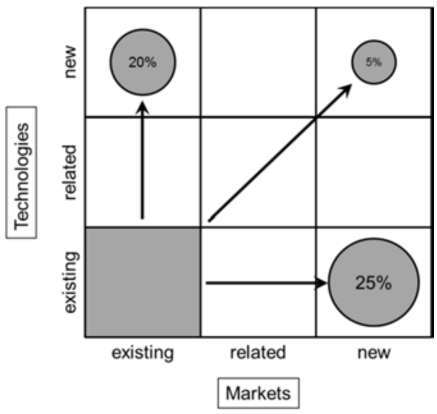

Figure 4. Diversification strategies with its chance of success (cf. [Koppelmann 1997])

Transferring Koppelmann's approach from a new product and its market to a single element or component within a system, instead of the market the term "application scenario" seems more feasible, which describes the influences on the system, all its boundary conditions and its functions to fulfil.
Bringing these two factors which correlate with the degree of maturity together with the dimension impact, a three-dimensional matrix can be outlined, in which different elements can be classified. As depicted in Figure 5 the matrix consists of three axes on which the three factors impact, the perspective technology and the application scenario can be plotted.
As mentioned, in this context the application scenario means the functions of the component to fulfil and all its boundary conditions. The technology describes the active principles, the used materials and production processes. Impact describes the connectivity of the component and its interdependencies.

Thereafter elements whose rating is close to the origin are characterized as uncritical, whereas elements with unknown technology, unknown application scenario and high impact are highly critical.

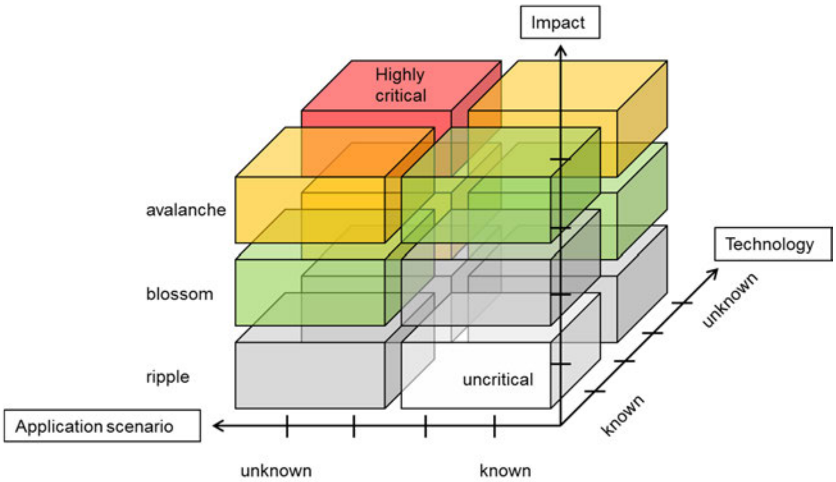

Figure 5. Criticality matrix

By classifying the elements of a system into this criticality matrix the designers are able to prioritize the appropriate validation activities in a way that the most critical components are validated first to increase the corresponding degree of maturity. With this approach it is possible to minimize the effort of validation activities while simultaneously shifting the changes to early phases also resulting in less effort due to late iterations (cf. [Weber 2009]).
In terms of usability of this approach and to increase the reliability of the results, the designers have to be supported methodologically in rating the three factors.

Technology and application scenario

The perspective technology and the application scenario can be rated by expert knowledge at least in a first step. Therefore the designers can search for similar technologies already used in-house or known application scenarios from predecessor systems. At this juncture there are two possibilities. On the one side it is feasible to have different specialists rating special components related to their area of expertise due to their deep knowledge about boundary conditions and technologies which are already known or new. This comes with comparably high effort. On the other side less engineers with a good overview and systems understanding could do the rating more efficiently but with of course less reliable results. The second option is advisable for a first rating which then can be refined by specialists afterwards. The rating can be done with a scale from 1 to 5 which turned out to be a good trade-off between being unable to cope with too many alternatives and having some increments to choose anyhow.

Impact

Compared to technology and application scenario the factor impact is hardly to determine by a single person without the help of a tool regarding the complexity of all the interdependencies in between e.g. a mechatronic system. Therefore a method and tool for identification of the impact of a single element on the rest system has to be developed. The impact is determined by the interdependencies between different elements. To rate the impact of a single element, a way to detect the interdependencies from this element's point of view has to be found. A tool which can support this task is a Design Structure Matrix (DSM) (cf. e.g. [Steward 1981]). This tool and how it can be used for rating the impact is described more in detail in the following.
"A DSM displays the relationships between components of a system in a compact, visual, and analytically advantageous format" [Browning 2001]. In Figure 6 an example DSM is shown. Every mark, except the diagonal, signifies the dependency of one element on another. All marks in a column represent the other elements the element in that column depends on (input sources), whilst reading

across a row reveals which elements are influenced by the element in that row (output sources) [Browning 2001].

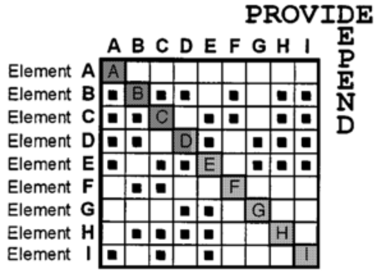

Figure 6. Example DSM [Browning 2001]

Steward stated, when a variable change is made or considered, going across a row will show the designers what other variables will be affected. Then they can go across these rows and so on to capture the resulting changes which have to be considered [Steward 1981].

It is obvious, that the quantity of marks in a row stands for the number of impacts from the element in this row to further components which is called the “active sum”. Compared to that, the quantity of the marks in a column stands for the influence from other elements on the element in that column and this is called the “passive sum”. Combining these two sums of a special element by multiplication leads to the criticality of this element which shows a component’s degree of integration to change impacts in the system [Lindemann et al. 2009]. According to that, the criticality is low if one of the sums is close to zero. This is reasonable since an element with a low active sum does not propagate a change – Eckert et al. speak about “absorbers” in this context [Eckert et al. 2004] acc. to Jarratt et al. [2005] – whilst for an element with a low passive sum the probability of an incoming change is low and therefore the criticality drops.

This value for criticality from a change propagation’s point of view can be used to rate the factor “impact”. It is feasible to create the DSM in discussion with engineers from different departments since a single engineer cannot see all the interdependencies from his point of view. After calculating the impact by multiplying the two sums the resulting value has to be normalized to the same scale as for the technology and application scenario to ensure that all of the three factors are weighted equal.

Overall rating

To be able to classify the system’s components and therewith prioritizing the validation activities regarding the ones with the highest criticality the three single ratings have to be brought together. Multiplying the three factors would end up in a situation that one single rating close to zero would lead to a low overall rating with less effect of the other factors. This isn’t reasonable since every factor has to be taken into account. Additionally multiplying high-rated factors would lead to a disproportionately high overall rating. Hence it is more reasonable to sum up the three single ratings to get the overall rating and to be able to find a meaningful ranking.

Summing up in the following Figure 7 the combination of the different approaches and the derivation of the criticality as a characteristic factor is depicted.

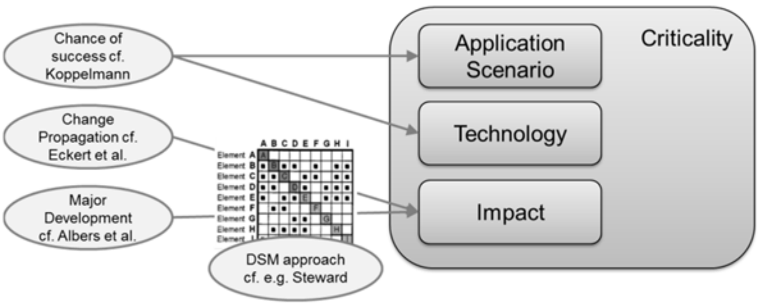

Figure 7. Combination of the different approaches

5. Application in engineering design practice

The application of the new approach was realized in a government-funded research project with one German OEM, several suppliers and two research institutes. The goal of this project is the development of a lightweight high voltage battery for plugin hybrid electric vehicles.

The research project is organised in a function-oriented structure [Zuegner et al. 2013]. The goal of this approach is to enable innovative concepts that exceed existing component borders. This lead to a matrix organization that provides cross-functional roles taking care of package, requirements and production and functional groups combined to ‘virtual components’ called:

- Casing
- Supporting Structure
- Thermal Management
- High Voltage Wiring
- Electrics/Electronics

At project start the virtual components consist of a specific group of technical functions based on the product generation n-1. Within the first concept phase, it is possible to switch functions within these groups. This permits flexibility in finding an optimal system concept and reduces the influence of common roles of the project partners. A switch increases uncertainty in some points due to new functions to fulfil regarding a special component. This is contrary to conventional development projects that are focused component-driven improvements and responsibilities.

In the first phase of the project, different concepts for the subsystems were developed and documented in Pugh matrixes (cf. e.g. [Frey et al. 2009]). These concepts have been rated with several criteria and an overall concept has been defined. Due to the attempt of the project team to find innovative solutions, the uncertainty in early phases was comparably high and a way to reduce the risk was needed. Nevertheless to validate every single subcomponent and part from the beginning on would need too much effort in terms of cost and time since prototyping and simulation is a long-lasting and costly attempt. Validation of the complete system with all physical components is planned not before the second project phase. On this account the team decided to develop a conceptual prototype for the early phase which includes only the most critical component concepts. Therefore the new approach was used to estimate the subsystems to realise as part of the prototype and thereby to reduce the uncertainty by well-aimed validation.

Out of the Pugh matrixes the single sub-solutions of the overall concept could be diverted. These sub-solutions have to be evaluated and classified with the criticality matrix (see Figure 5). In a first step the criteria application scenario and technology were rated by two members of the project team, one researcher and one engineer from the OEM with detailed knowledge about the systems design. For the assessment a scale from 1 to 5 was used, meaning 1 for well-known technology and application scenario and 5 for high uncertainty. For estimating the factor impact, a DSM with all of the sub-solutions was created. This was filled out by team members with more system understanding rather than special expert knowledge who are allocated in cross-functional-teams.

To be able to classify the sub-solutions in a reasonable way the resulting value for impact was normalized to the same scale from 1 to 5. To get an overall order in terms of priority in a first step all factors were weighted equal and summed up to get a value for criticality as explained in the previous section. This means the maximum possible criticality is represented by the value 15. The result is shown in figure 8. Therein the overall criticality rating is plotted for every single sub-solution. The black bars stand for the rating of the factor technology, the shaded bars represent the values of the factor application scenario, the white ones for the rating concerning impact. With this diagram, the designers can easily see the most critical sub-solutions which have to be validated in early phases of the development process. Additionally the single ratings are still available and traceable. As observable in Figure 8 the single ratings vary in a wide scope. Furthermore there are components with equal overall criticality but different single ratings. This is important information which can be used for the later conceptualization of the validation environment and test-cases etc. E.g. if the application scenario is unknown in particular, for validation especially the new boundary conditions and functions have to be considered in defining the test-cases.

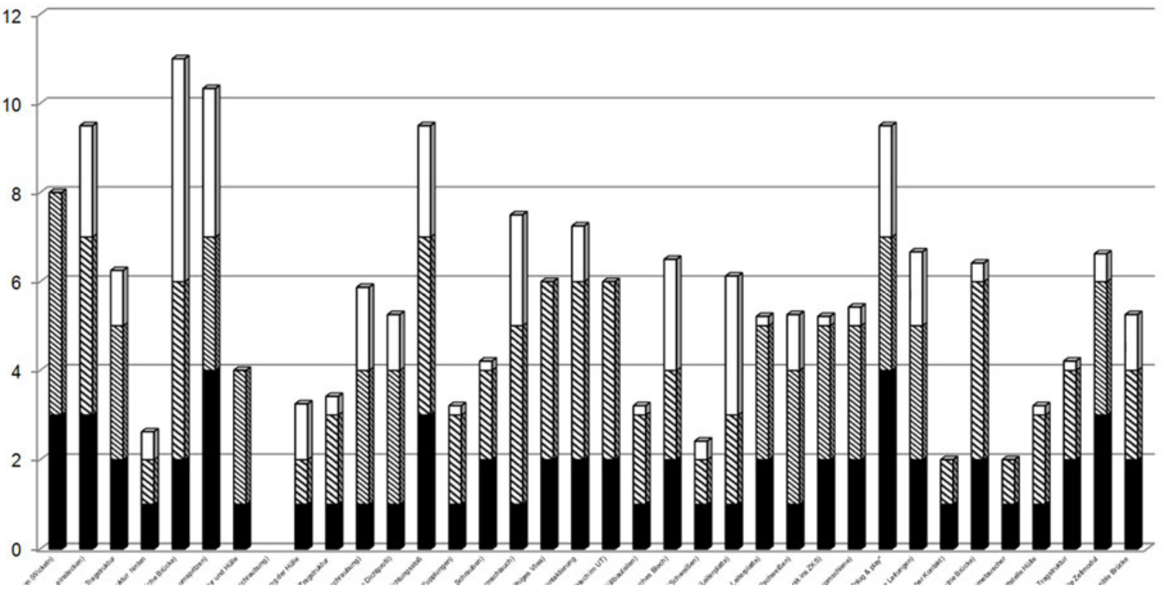

Figure 8. Criticality rating (technology – black, application scenario – shaded, impact – white)

As an example one of the most critical sub-solutions is explained and compared with an uncritical component within the special setting of the funded research project.

The subjects of matter in this case are the virtual components casing and supporting structure. Some substantial requirements regarding electric energy storage safety lead to high mechanical loads like 60g shocks in the case of a car-to-pole crash. The function of absorbing these loads was switched from the casing to the supporting structure, which protects the battery cells by introducing a design optimized to the specific loads and vehicle mountings [Wagner et al. 2013]. This functional switch adds up to less loads on the casing and a weight reduction. This fact leads to change of material for the casing component and a different geometry. With the presented approach this results in the following criticality rating for the component "casing":

- Technology: known
- Application scenario: known
- Impact: ripple

The technology is already known as the new material and production process are mature and already in use. The application scenario is also known because existing components within vehicles have the same boundary conditions as the new component setting (geometrical and loads). The DSM furthermore reveals that the impact on the system is low, because the new virtual-components has just one interface with the supporting structure and hence does not severely influence the system. That is why this component concept has a minor validation priority.

On the other hand the virtual component supporting structure integrates more functions and thus gets more critical for the system. Based on a new mounting procedure the component gets an additional parting line. This division of parts leads to a second sealing gasket that is oriented in 90° to the first three-dimensional sealing resulting in the following assessment:

- Technology: known
- Application scenario: unknown
- Impact: avalanche

On the one hand there are technologies coping with similar tasks but on the other hand there is no known application in the specific set of requirements. Particularly the analysis of the DSM affirms the central role of the supporting structure within the product system. This is a result of the switching of functions, which leads to a high innovation potential but also to high risks. As the overall system concept premises the considered solution, it would have an enormous impact on other components and production in the case of malfunction. For this reason, an essential attention is directed to validate this interface in a preliminary sample phase with a conceptual prototype.

6. Discussion

Comparing the results in fig. 8 with an intuitional selection by a separate engineering team showed a good compliance. One exception was found in a component concept estimated as very critical with the new approach but did not have the highest priority for the engineers until that time. As a consequence the priority was raised and it was set on action list.
The good compliance to the intuitional selection verifies the results of the method. The benefit lays in the methodological guided procedure which also is easy to use. The method offers traceable and complete results. This prevents forgetting critical aspects like the one exception already mentioned. The methodological approach offers a basis for discussion and documentation. Especially discussing the DSM more precisely the influences between different elements/components in an interdisciplinary team increases the systems understanding. Additionally the approach serves as a justification for the validation activities. Hence the team does not perform a special validation activity due to its subjective estimation but rather due to a methodologically acquired result.
Though to rate the three factors implies some effort, especially to fill in the DSM is rather time-consuming. This decreases the effort-benefit ratio which is an important factor concerning acceptability.

7. Conclusion and outlook

Major iterations in the late development process lead to high costs. Therefore validation activities should be part of the process as early as possible. Nevertheless every development process itself has requirements to meet as e.g. budget and time limitations. Hence it is not possible to validate every single sub-solution in early phases. Therefore a methodological support is needed to prioritize the validation activities.
The presented approach is based on the idea that the most critical sub-solutions have to be validated first with high priority. For determination of the criticality three factors were described and combined, which build up a criticality matrix – the uncertainty concerning application scenario and the used technology and the impact. By rating the three factors, the designers are able to estimate the criticality of a certain solution. To support the designers in rating the complex factor “impact” a method was developed using Design Structure Matrices (DSM). A more methodological approach to rate the two factors application scenario and technology by a future extension of the method would lead to a higher reliability of the results compared to the rating of the first attempt which was based on experience and estimation.
As a conclusion it was found out, that the results of the approach (see Figure 8) match very well to the assumption of the engineers based on their knowledge and experience. The benefit lays in the methodological procedure which ensures completeness consideration of all elements. Additionally the results deal as documentation, as a basis for team discussions and for justification of the performed validation activities.
To reduce the effort for rating the three factors and thereby to enhance the effort-benefit ratio of the approach an idea will be traced in future work to derive DSMs out of SysML-models. If the engineers use an overall SysML-model for their development work which includes the information about interdependencies between different sub-systems a DSM could be easily generated with a special tool. This would minimize the effort of creating the DSM.
Additionally, further research work has to be done concerning the possible improvements by different weighting of the three factors while bringing them together to the overall rating. Going further maybe it is reasonable to vary the weighting factors between products from different industrial sectors, different product generations or even between different development phases.
If the prioritised sub-solutions for validation are determined with this new method, the engineers need support for planning and executing the respective validation activities. Therefore methodological assistance is needed for the development of the validation environment, the determination of test-cases and the most efficient combination of virtual and physical sub-systems and models for a certain purpose. Therefore the data gained in the presented approach about interdependencies between different components and uncertainty about the technology or application scenario can ideally again be a valuable input.

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