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# INTEGRATION OF CUSTOMERS' REQUIREMENS AND DFX-APSECTS AND THE DEGREE OF MATURITY IN A PROPERTY BASED FRAMEWORK

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## 1. Introduction

The consideration and integration of customers' requirements are one of the most important tasks of a product developer. But the increasing individualisation of the customers' preferences forces the developing engineers to provide a huge range of variants to fulfil all these wishes and allowances.


**Figure 1. Number of variants of car producer**

Additionally the intersection of technical products with mechanical, electrical and software based solutions as well as global shared development departments have led to very complex products and development processes.
Considering the area of conflict consisting of costs and quality and time and innovation it is difficult to efficiently develop a product with a sharp and clear defined property profile, which matches the customers' requirements as well as the requirements resulting of the development process, without time and cost intensive iteration loops.
Therefore it is vitally to evaluate a degree of maturity in order to monitor the development process. Consequently the causes of iterations can be noticed in the early stages of development and

appropriate steps can be triggered to avoid expansive iterations. But this affords a degree of maturity, which describes the customers' requirements as well as the process based additional requirements and which can easily be calculated by the actual product representations during development process. The only continues product representations during development are the behaviour and the properties of a product. These are specified during the early phases of development and are relevant for the approval at beginning of the production.

Thus a property based framework is presented to combine the detailing of customer requirements down to technical properties and to characteristics under consideration of the so called DfX-aspects with a integrated monitoring of a degree of maturity and iteration management.

Each aspect or approach stands for its own and has certainly its own benefits and potentials. But – and this is the main topic of this paper – they are strongly depended on each other and this framework enables it to integrate these single aspects and to connect them on the base of properties and characteristics.

## 2. Fundamentals in product development

This chapter introduces the state of the art. Beginning with the definition of properties and characteristics a short survey of the degree of maturity should be given. Afterwards the relevant process models for this approach as well as the term "*DfX*" will be explained.

### 2.1 Properties and characteristics

First an exact definition of the terms *"property"* and "*characteristic"* should be given. The approach of the characteristic property modelling (CPM) and following approach of the property driven development (PDD) developed by WEBER ET AL. distinguishes between so called characteristics $C_i$ and properties $P_i$ to combine the physical characteristics of a product and its parts with the resultant properties and functions. In this context characteristics define the structure or the appearance or the consistence of the product. While characteristics can be defined directly by the designer, properties describe the behaviour and the function of a product [Weber 2005]. These two classes are connected by two main relations, which are corresponding with the two main activities during product development: During analysis product properties are determined based on given characteristics. During synthesis characteristics are assigned in order to fulfil predefined and required product properties. The CPD approach links characteristics and required properties and actual properties and external conditions with relations. The PDD approach - which has been established on CPD - compares the target or required properties with the actual properties as a measurement of the development status (degree of maturity). The result can be seen as a representation of the shortcomings of the actual design. The development process ends, if the divergent of the target and the actual properties runs against zero or - in other words - if the actual properties matches with the target properties [Weber, 2005].

### 2.2 Product's degree of maturity

The product's degree of maturity is the degree of fulfilling the customer's needs in consideration of additional requirements resulting due to the choice of a certain solution. This definition displays an advanced comprehension of the term "product's degree of maturity" and takes into account, that there are more properties than just the customer's requirements relevant when safeguarding a product being developed. In connection with this, it is important to understand, that monitoring the progress of the product development process by means of capturing consumed time and caused costs does not allow any assured statement about the product itself. To assure the quality of the product already during development period, it is essential to supervise and to safeguard the product's degree of maturity separately. In this contribution the term "product's degree of maturity" is seen as performance of a product related to its use. Hence, the product's degree of maturity is the captured state of the product concerning defined indicators at an arbitrary moment. Due to iterations, changed target values, unexpected problems and changing indicators during development, the product's degree of maturity does not proceed linear but is wavering in reality.

**2.3 VDI 2221 AND 2206**

The described complexity as well as the pressure regarding time and cost and innovation has led to the development of a huge range of methodologies supporting the product developer. PAHL and BEITZ ("*planning, conceptual design, embodiment design, detail design*"), EHRLENSPIEL ("*Vorgehenszyklus*"), LINDEMANN ("*Münchner Produktkonkretisierungsmodell*"), SUH ("*Theory of axiomatic design*"), WEBER ("*CPM/PDD*") and many more developed different models to define and to explain the important procedure steps during development [Pahl/Beitz 2007]. The VDI 2221 "*Systematic approach to the development and design of technical systems and products*" has been introduced in 1993 on the basis of the so called „European school".

The VDI 2206 "*design methodology for mechatronic systems"* is a mechatronical approach. It merges different domain specific guidelines together and deals with the development of a modern mechatronic products. Moreover it describes the development process as the detailing of requirements, the development within the single disciplines and the aggregation of analysis. Therefore it creates an essential basis for the communication and cooperation of experts of different disciplines, who are involved in the development process. Here the most problems occur during development. The guideline promotes interdisciplinary cooperation, which has proven to be an outstanding factor in successful development of mechatronic systems [VDI 2206, 2004].

**2.4 Design for X**

In literature three main definitions of DfX are found [Bauer, 2009]:

V. Hubka sees DfX as a knowledgement system, which safes expertise of engineers [Hubka 1995]. The expertise contains, how special properties of technical systems can be achieved. By the definition of M. M. Andreasen Design for X is a procedure, where methods and knowledge are used to design a product relating to the criteria "X" or the domain "X". The free parameter "X" stands for a phase in the product life cycle or for a main property of a product [Schäppi 2005]. According to Huang DfX is „making decisions in product development related to products, processes and plants". Considering these different aspects of product development is according to HOLT one of the most important precondition for successful concurrent engineering [Holt 2009]. In the sense of Design for X the DfX-guidelines, methods and -tools should be provided to the developer as support for the definition of characteristics and their dependencies. DfX-guidelines are made available to developers, in order to support decision making and the definition of characteristics. For instance during the design of a ceramic component guidelines like "avoiding stress peaks", "avoiding material accumulations" or more detailed instructions in the later phases of product development like "avoiding angles and sharp edges", "paying attention to constant wall thickness" or "avoiding cross-sectional jumps" can be provided.

DfX-Methods are procedures to use successfully DfX-guidelines. DfX tools are the practical DfX methods, mostly software tools like Pro Mechanica or Nastran.

## 3. Property based framework

The following section introduces a property based framework as basis for further investigations. One the one hand the theoretical considerations about properties and characteristics are enlarged by the assessment to the product structure. On the other hand the VDI 2206 defines a procedure, which links the customer requirements via system design to the domain specific realisation of single components. This system design represents a hierarchical downgrading of product specification to system or module specifications and down to component specifications. Afterwards each domain starts designing with use of their specific development methodologies. The integration and validation is the final step of this process. The itemised tests and simulations can be hierarchical aggregated. This means first the components are tested afterwards the system and finally the whole product is tested (see Figure 2).

In the approach of property shared products development single structures layers – symbolising different structure hierarchies - are integrated to this model [Lindemann, 2007]. Beginning with the requirement structure, which represents the view of the customer, the target product properties are deduced, which specify the product in form of technical properties (target product properties). During system design the requirement structure is transformed into a functional structure and into an effect structure, which defines single physical solutions. These physical solutions or modules can be described by target module properties. The detailing of the effect structure leads to the part or assembly structure, where single parts and components are specified. These parts and components are described by target part properties and are configured by defining characteristics. Therefore a property hierarchy can be deduced, whereas the property levels or classes can be described by the single structures. Oriented at the target part properties the domain specific development – as it is described in the VDI 2206 – can start. The target module properties can be used to synchronise the results of the single domains. Afterwards the domain specific testing and simulation begins to evaluate the actual part or component properties. During system integration parts or components are tested. After that simulations on the assemblies are done, for example to investigate the stress of the whole product under certain situations. This leads to a large mass of several discipline specific evaluations and evaluation results. A complete physical or virtual prototype of the whole product – like it is proposed in several functional mock up approaches – is hardly available in early phases. Therefore individual evaluation results have to be summarised. Consequently the test or simulation results – the actual properties – have to be aggregated in the same way up to the actual or realised product properties and behaviour as the customer requirements were detailed down. Consequently, to achieve realised product properties, the test or simulation results have to be aggregated in the same way as the customers' requirements were detailed.

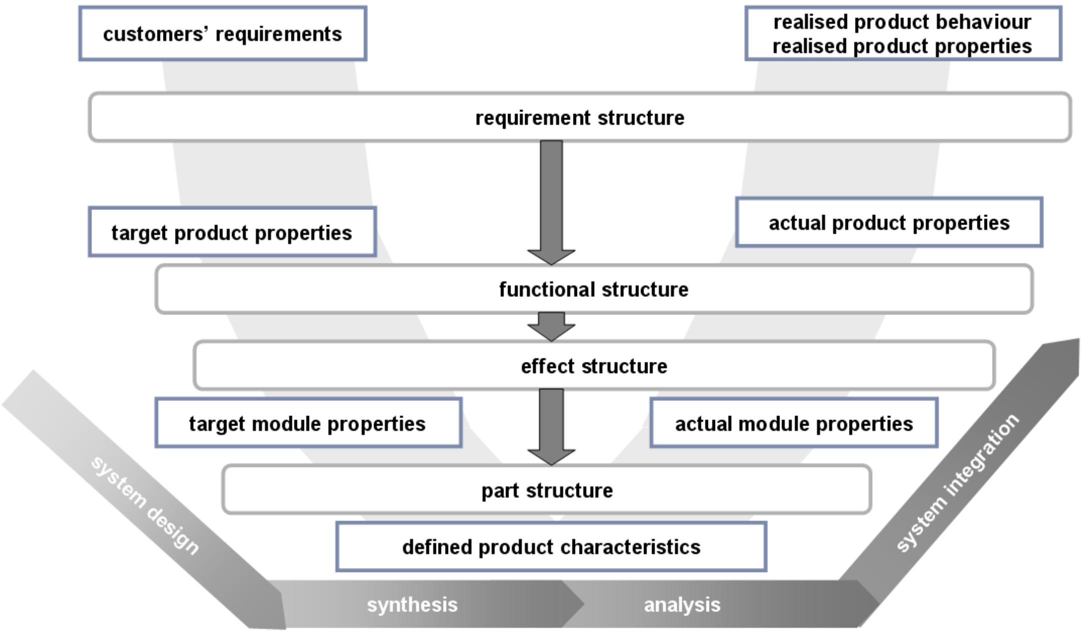


**Figure 2. Property based process model**

## 4. Integration of customers' requirements and DfX-aspects and the degree of maturity in the property based development

The following chapter describes three aspects of product development and their relation with the property based framework. First the detailing of requirements is presented. The integration of the DfX-aspects enables the definition of an holistic concept of the degree of maturity. Afterwards the results of this degree are used to manage iterations and their consequences.

### 4.1 Property detailing

To calculate the described degree of maturity two main tasks have to be fulfilled. On the one hand customer requirements have to be detailed to technical criteria, which can be evaluated [Akao, 1997]. As this step can be processed by a lot of different development departments, it is impressively necessary to document and to communicate the product requirements and the target properties. In first step customers' expectance and wishes can be deduced to property and behaviour aspects. The approach should be clarified by an example: A customers' requirement could be the reduction of the injury risks in case of a crash. Property aspects can be e.g.: product weight, design or stiffness. The behaviour aspects – like safety or the driving comfort of a car - describe the behaviour of a product under certain circumstances. This means that behaviour aspects are strongly depended on the mode and conditions of use. Within a next step the property and behaviour aspects have to be detailed. For example the safety of a car can be detailed down into active and passive safety. Furthermore it can be detailed into the crashworthiness of the occupant of the driver and the co-driver. To define these behaviour aspects its necessary to model the mode and conditions of use in a kind of test scenarios. This is for example a NCAP front crash with 64 km/h by testing vehicle. By defining the influences of the manoeuvre and the human and the environment a complete description of the test scenario can be assembled to represent a certain mode or condition of use. But this exact definition of the analysis situation is not enough to define specific target properties, which can be evaluated. In difference to the property aspects which can be directly defined as assessment criteria, behaviour aspects in generally have to be measured as tracked state variables. The assessment criteria can be defined via discretization or via calculating the tracked state variables. A tracked state variable in crash tests is the head acceleration of the occupant, which gives information about the active forces and the induced injuries. There are limits for the maximum head. For example the head acceleration should not be more than 72g. This value represents the assessment criteria. The results are well specified assessment criteria on the level of the whole product (target product properties) (see Figure 3).

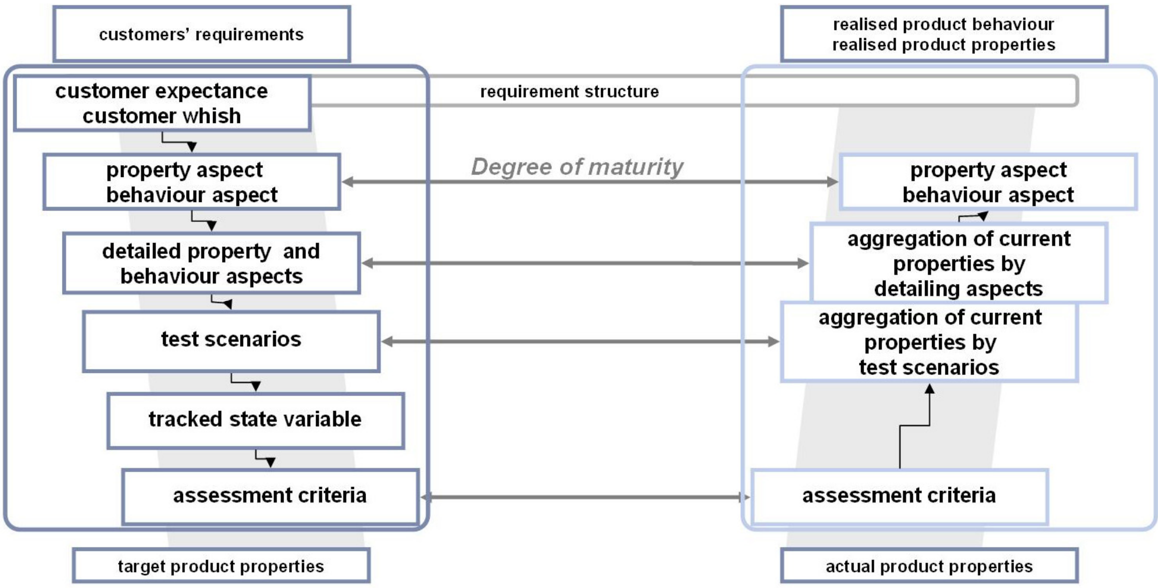


**Figure 3. Property detailing**

Especially in the early phases of product development these are no physical prototypes are available to evaluate the holistic behaviour and property profile of the product. Therefore it is necessary to aggregate and summarise single evaluation results from different testing and simulation methods to evaluate the current degree of maturity. Moreover it is necessary to do this hierarchical aggregation in the same way up like the property and behaviour aspects were detailed down. Thus the current properties have to be aggregated first by the test scenarios. Afterwards they have to be aggregated by the detailing hierarchies to get the current realised product behaviour and property profile.

But this procedure requires and enables a predefined sequence as well as integration of the simulation and testing methods and tools. Especially simulation tools, which are the earliest tools in the development to calculate properties, have to be integrated by a connection of the requirement management and the simulation management. This should enable to exchange the target properties –

the target assessment criteria – on the one side and the simulation results – the actual assessment criteria – on the other side to generate a degree of maturity.

### 4.2 Definition of product characteristics according to Design for X

The product development process is characterised by two steps, the synthesis and the analysis [Weber, 2005]. At the beginning of the product development process the engineers get the target properties of a product, which have to be transferred in characteristics. In the synthesis step product developers define characteristics of the product. Actual properties of the system result in these characteristics. In the analysis step the actual properties are analysed. It is important to check, if the actual properties are the same as the wanted target properties. If not, iterations have to be done in several synthesis steps. In

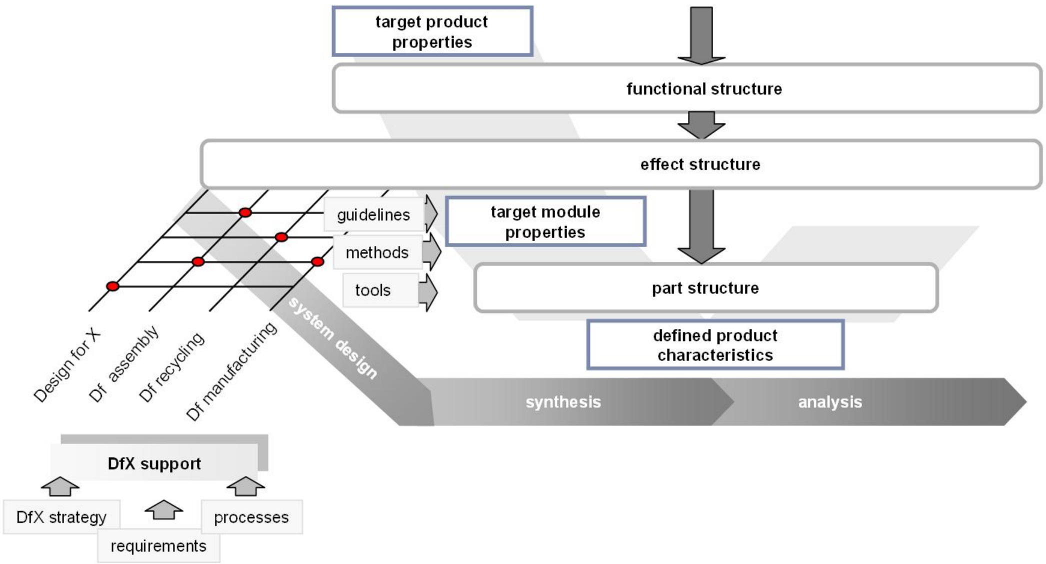


**Figure 4. DfX support in the synthesis step**

order to avoid iterations and unnecessary costs, a DfX support to product developers is essential.

The main task of DfX is to support decision making in the synthesis step [Schäppi 2005]. Here target properties are transferred in suitable characteristics, which define actual properties of a product. During the product development process a large number of decisions have to be made, which influence the product and its properties like the selection of the material therefore the dependent method of manufacturing. In the synthesis step it is necessary to support the product developers by suitable methods and guidelines depending on the process step and the context of product development. Therefore product developers have a large number of methods and process support. The connections between the processes in an enterprise and the product development have also to be considered. But even a situation specific support to the engineers related on their activities in the product development process makes it possible to avoid iterations and to save time and costs (see Figure 4).

First the target product properties are deduced from the requirements. Product developers have to define the functional structure and the effect structure. The definition of the effect structure depends on the chosen DfX aspects like manufacturing, assembly and recycling. If for example the function "transforming forces" are needed, the definition of the target module properties is e.g. depending on the used manufacturing method. For instance the gearwheels can be coasted or be milled. It depends on the requirements resulting from core competence of the enterprise, the plants which are available or the make or buy decisions. So the product characteristics like geometry, material and surface of the gearwheel are different considering different "X"s. The definition of the product characteristics also depends on the DfX strategy. The "X"s have to be checked, which are important. Furthermore the weighting of the "X"s must be clearly recognisable. Thereby the use of a DfX strategy is helpful. A DfX strategy is formulated on the basis of weighted DfX criteria. So aims can be made via the selection and the weighting of suitable criteria in the product development. The creation of a strategy is pointed up in. The integration of the DfX approach in the early phases of the product development process makes it possible to keep important development conditions in mind. By the programme "Balance 3D", which is described in detail, the product developer receives a computer assistance during the early phases of the product development to support the handling of design iterations [Bauer, 2009].

### 4.3 Evaluation of the efficiency of a considered iteration

As mentioned above, in this contribution the behaviour of a product in connection with the additional properties is seen as the relevant measurement to assess the product's degree of maturity. To assess the behaviour in different conditions of use - and thus to evaluate the degree of maturity -, two important things have to be known: On the one hand the mode and conditions of use and on the other hand the product's properties. The mode and conditions of use are a result of the later use of the product, whereas the product's properties can be determined from the configuration of characteristics by conducting different analyses. By comparing these realised properties with the required properties it gets possible to evaluate the product's degree of maturity. As consequence of the introduced definition of the product's degree of maturity as an value comparing the actual an the scheduled state of products properties, in case of new requirements or changes of boundary conditions a decreasing product's degree of maturity is possible. This decrease can be seen as an appropriate indicator for the necessity and thus as a trigger for conducting a design iteration. Otherwise, successfully conducted design iterations will result in an increasing product's degree of maturity.
As shown in [Krehmer, 2009], these dependencies between the product's degree of maturity and design iterations allow evaluating the efficiency of any design iteration:

$$efficiency\ of\ considered\ iteration = \frac{degree\ of\ maturity\ after\ iteration}{degree\ of\ maturity\ before\ iteration} \quad (1)$$

The degree of maturity is assessed for the actual state of product before the iteration is considered. Then the degree of maturity after a certain considered iteration is predicted. Therefore for example two alternatives of design iterations A and B can be checked. The estimation of alternative A could for example indicate a better degree of maturity after the design iteration as the estimation of alternative B. So the efficiency of alternative A is better than the efficiency of alternative B. Product developers can be supported in decision making with this consideration. This efficiency of design iterations indicates the relative change of the products degree of maturity that is reached by the considered design iteration. Thus it is an appropriate way to compare two or more considered design iterations and can provide support for the choice of those product changes that result in an increasing product's degree of maturity.
Furthermore, the property based process model with its layers allows a classification of design iterations: In case of a identified target property, which is not achieved, the developer will conduct a design iteration by changing characteristics or by determination of new characteristics. This kind of design iteration is marked with number 1 in figure 5. If a change of characteristics is not sufficient to lead to successful execution of a design iteration, the developer has to consult the next escalation level and has to reconsider the part structure (iteration number 2). If this redesign of part structure leads to an increased degree of maturity, the chosen design iteration is to be denoted as successful. If the change of the product structure did not lead to the desired result, the property based process model (see Figure 5) keeps some further escalation levels: The further kinds of design iterations (marked with number 3 to 5) are leading the developer step by step to higher escalation levels having more and more significant consequences. By leading step by step from characteristic level (1) to part structure level (2), to effect structure level, to functional structure level and finally to the requirement structure level the developer gets support to conduct the - dependent on the situation – smallest and thus most effective possible kind of iteration that is just extensive enough to promote the purposeful execution of necessary design iterations. These levels are to consider as a framework of successive conduction of

design iterations, in which the developers should always access the smallest possible level to minimise the resulting fallback.

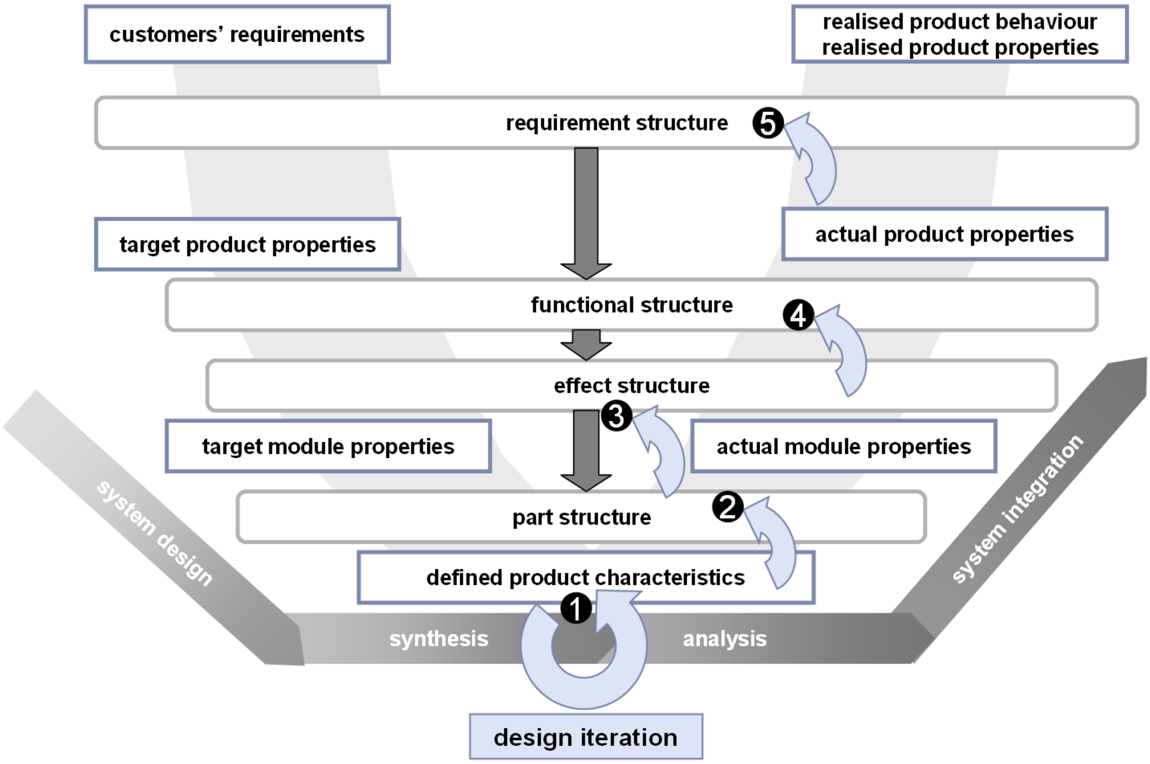


**Figure 4. Iteration steps during product development**

## 5. Benefits and potentials of a holistic property based description of the product development

In relation to the property based framework three different aspects of the development process were detailed and described. Starting with the detailing of properties during the requirement specification phase the influences of DfX on the target properties were shown afterwards. Finally the calculation of the degree of maturity and the management of iterations were presented.

Properties – different to the geometry - can be seen as common indicators of the product development process for different disciplines working on the same development project. Therefore different disciplines as well as different process phases can be synchronised by defined target properties. Moreover the definition of properties and characteristics on the different levels of the product structure enables a continuous and transparent description of the product. By the integration of the DfX–aspects the influences of the whole lifecycle can be considered. During the detailing of behaviour and property aspects the enterprise strategy as a kind of the DfX-strategy strongly influences the quantitative value of the target product property. A company, which has a "green" enterprise strategy, has to define lower emission values than a company, which wants to demonstrate a "cost-efficient" strategy. Therefore DfX–aspects have to be considered even in the early phases of development. After the definition of the functional structure of the product the concrete effect structure has to be chosen to fulfil the target product properties with certain module solutions and therefore with properties. But these are depended on the DfX–aspects, too. For example the stiffness of a blank sheet is depended on the production method. Thus the integration of the influences of whole product lifecycle can – and has to - be realised by the consideration of the DfX-aspects at the definition of the target product- and module- and part-properties. Consequently the solution space can be limited and the developer can be supported during synthesis.

Moreover the DfX-aspects lead to new target properties, which have to be evaluated: If a machine needs heels for transportation the load capacity of these heels have to be validated, too. Therefore only a definition of the degree of maturity, which integrates the target properties resulting from customer requirements as well those resulting from the DfX-aspects, describes a meaningful and complete status of the development project. Additional the allocation of guidelines in context of the effect structure enables – together with the described detailing of the customer requirements - a traceable method to define the way from the product requirements to the part characteristics.
On the other side the degree of maturity enables the developer to check if the customer requirements as well as the DfX-aspects are fulfilled or not and if measures have to be taken. The described iteration management, which is based on the degree of maturity is supported by this approach, too. By the definition of different levels and a hierarchy of properties the iteration activities can be allocated to this different levels of properties and characteristics. In spite of this iteration activities can be allocated to different structure levels. Consequently it is possible to classify iterations according to the plane of action.
The developed property based framework is validated at an industry partner within the automotive industry. The following six property aspects are chosen to be monitored by the means of the new framework: crashworthiness, tonal quality, axial dynamic agility, interior design, recycling, sitting comfort in front. These aspects are detailed to target properties. The influences of customer requirements, DfX-support and iteration management are investigated.

## 6. Conclusion and further work

Summing up this paper an holistic property based framework was shown, which combines– oriented at the VDI 2206 - the requirements with domain specific characteristics and with the resulting product properties. Three aspects – the detailing of properties during the requirement specification and the integration of DfX-aspects and –guidelines and the calculation of a degree of maturity as well as the management of iterations, were outlined and described. Afterwards the relations were highlighted and integrated into the framework, which will be evaluated at the industry partner.
Some objectives of the further work will be the detailing process has to be concretised and validated within a real product specification. Moreover the connection of simulation and test methods has to be investigated to have fast and significant actual properties for the calculation of the degree of maturity, In this context it will be interesting to investigate the influences of the validation methods and the kinds of product representation on the result of this degree of maturity. Therefore it is inalienable to add a factor of uncertainty to the products' degree of maturity.
An other goal is to provide the correct elementary instructions and methods during the product development process at the correct time to the developer. It is important to support the product developers' decision making and thus they to the optimum for the product and for the processes. Further on it should be analysed, which synergies and interactions result from the choice of the DfX strategy with other influences on the product development, like existing processes in an enterprise, the business philosophy or the market positioning. Therefore the network of existing processes in an enterprise has to be considered.

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