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PRODUCT STRUCTURE MANAGEMENT AS THE BACKBONE OF ENGINEERING DESIGN: EXPLORATION OF A REFERENCE MODEL

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1. Introduction

In automotive industry, systems engineering, and especially product architecture design, gain more and more in prominence in order to cope with the challenges of internationalization, highly variant product portfolios and niche markets. The rising complexity of portfolios and the need for extensively customized products are considerable drivers for this development. To keep a product portfolio manageable and efficiently adaptable to changing market needs a lot of effort is required to adapt the organization, roles, responsibilities, tools and methodologies.
In this paper, an approach of integrating architectural design activities using a new developed product structure model as a backbone in engineering design processes is proposed. It supports the architectural design role in a company to coordinate efforts to design, maintain and make use of systematic product architecture. That provisions the management of complex product portfolios. The concept was developed and is currently being implemented with a large German commercial vehicle manufacturer.

1.1 Scope and goal of this research

Product Lifecycle Management (PLM) and Product Data Management (PDM) integrate different processes across a company via a common IT system and aligned methods. Product Data Management systems are the most important part of PLM strategies, as they serve as its key component to manage all product data and related workflows. PDM systems make necessary and relevant product data available in each part of the design process and for each participating role throughout the whole life-cycle of products. A consistent product structure model forms the core to such a system [Arnold 2011]. To this product structure model, representing the architecture of the products that are managed in the PDM / PLM system, all additional data such as CAD files, process descriptions and more are associated.
With a regard to product architecture, several methods and strategies have been developed in the past, giving answers to single reasons for increasing complexity, such as modularization of products or platform strategies. With the introduction of such an approach, however, the question of *how a systematic product structure can serve as a backbone for engineering design activities* and therefore as a process integrator is complex to answer and needs a framework, also to ensure the integration of relevant stakeholders into the design of the product structure.

1.2 Context of this research and research approach

The central use of a systematically planned product architecture as a backbone for the design of complex products is widely recognized [Lindemann 2007]. In this research, such an approach has been formulated as the product structure template that is part of the partner company's PDM/PLM system [Kreimeyer 2012]. Therefore, it is not explained here in detail. This is why, in this context, the product structure model itself is considered a given reference that is not in focus.
This research is part of a joined effort to generate a systematic, PLM-supported systems engineering process for highly variant products that are produced primarily in an assemble-to-order process based on modular product architecture. The project is run in a collaborative effort between academia, consulting, and a commercial vehicle manufacturer.
The research approach is based on Action Research. As such, the approach shown was developed out of the continuous observation, reflection and improvement of an implementation project for a PDM / PLM system in industry. This effort was accompanied by a comprehensive literature review and complemented with expert interviews and industrial best practices. The implementation of a product structure management at the truck manufacturer started with the methodology development. This phase is followed by the IT implementation, a validation phase and the go-life of the system. The results of the first phase – the methodological approach – are presented in this paper.

1.3 Structure of this paper

Chapter one introduces the research approach, before in chapter two a summary of the state of the art concerning product structure management is given. In chapter three the reasoning for a reference model is explained that is outlined in the subsequent chapter four, including the application in industry. Section five discusses the approach and gives an outlook to further work, before paragraph six concludes this paper with implications for research and industry.

2. Architecture design and product structure management: State of the art

On search for an appropriate product structure for a commercial car manufacturer, scholars in the field of product architecture offer helpful definitions as a starting point. [Ulrich 1995] defines product architecture as a way in which "the function of a product is allocated to physical components". He separates product architecture into the three aspects of (1) how the functional elements are arranged, (2) how the functional elements are mapped to the physical components and (3) how the interfaces between interacting components are specified. Nevertheless, the scope of an architecture design entity in a corporation is broader and there is an obvious need for a reference process.
When [Crawley et al. 2004] define system architecture as "an abstract description of entities of a system and the relationship between those entities", they waive to limit their definition to components, functions and interfaces. However, the complexity of the products themselves and variety in the product portfolio of the commercial vehicle manufacturer necessitate an architectural approach not on the "one-product-level", but taking the product portfolio itself into account.
Of course, also product families can have an architecture when there is certain commonality within the family, described by [Martin and Ishii 2002]. After them, the implications for an architecture on this level are that "different products have common arrangements of elements, common mapping between function and structure, and common interactions among components".
Also [Jiao et al. 2006] describe approaches how to design product families efficiently on an architectural level. But they also give no advice how to integrate these approaches on a corporate level.
Although, [Schuh et al. 2008] developed a comprehensive reference process for Product-Life-Cycle Management on an abstract level, they do not provide any integration of a consistent product structure with the processes they suggest. Therefore, we postulate the necessity to have an integrated product structure as a backbone for all processes of an architecture design entity where all changes to the structure are entered sustainably and consistently. Otherwise, without a holistic and established product structure, all innovations and improvements to the product portfolio would start from scratch and not in an iterative improvement of the portfolio.

Systems Engineering is a promising method to translate market needs into large scale engineering projects resulting in products, which are competitive in the market. Product Architecture Design is one of the key competencies to perform a development project successfully [Haskins et al. 2006]. In the handbook of Systems Engineering of INCOSE, the architectural design process follows on the requirements analysis process and is the antecedent of the implementation phase. Depicting the development process in the V-Modell, architectural design is also responsible (horizontal in the V) to prepare input for the integration and verification phases. The main activities in the architectural design are after INCOSE:

- Definition of logical architecture
- Partitioning of system functions
- Tracing of logical relations between requirements, functions and system elements
- Evaluation of off-the-shelf system elements
- Evaluation of alternative designs
- Documentation of interfaces
- Development of an integration strategy and the
- Definition of verification and validation criteria

While these recommendations serve as an abstract orientation, the experience in our work at the commercial car manufacturer showed that the definition of these tasks has to be adjusted individually to the needs of a company and aligned to the corporate strategy. In our study, we revealed in communication with expert at the truck manufacturer in particular that the consistent definition of a product structure is a crucial backbone to integrate the activities of product architecture in the processes of the company.

We adapted several ideas from literature in our approach. However, a suitable reference process for commercial vehicle manufacturers that integrates a consistent product structure model does not exist in literature. Providing a real life example from industry in this paper, we want to expose the value-add of the interlocking of the two aspects reference process in combination with a product structure as a backbone.

3. Reference model for product structure management

As every company's design process is specific to the company, a generic reference model was designed that serves as an overall framework for product structure management. Such a general framework is considered a valuable starting point for the vehicle manufacturer as a high level reference was needed to design and deploy, as a company-specific reference model would not have been able to provide a checklist that was sought to ensure a complete and consistent approach.

Several generic reference models and frameworks from the automotive industry served as starting point for the development of a reference model specific for the industrial vehicle industry. The automotive reference models have to be adapted, as passenger cars differ from commercial vehicles in a number of aspects. Firstly, commercial vehicles, especially for the public sector, are partially designed to order, based on bidding processes, and product structures have to cater for this aspect with regard to the flexibility necessary to such adaptations. Secondly, configuration contexts for commercial vehicles are more extensive than passenger vehicles as, on the one hand, more options are available (typically, about 400 for a truck, about 100 for a passenger car) and, on the other hand, these options impact the package and topology (i.e. components can be placed throughout a vehicle for e.g. varying wheelbases, something that is rather uncommon to passenger cars). Lastly, processes in commercial vehicle business are centered on the management of modular kits that, often, take shape at a high level of aggregation. The design, maintenance and use of the modules are therefore an important driver for the design of the reference process.

In our approach, we suggest a product structure model (for details c.f. [Kreimeyer 2012] that has been developed in the commercial vehicle branch as the backbone in engineering design processes. The term backbone refers to the role of the product structure model as the central construct in the development phases. Thereby the model predetermines steps and serves an integrator in processes. In

this section, we outline a reference model explaining the generation or further development of objects of the product structure model in early stages of a development process.
The basic approach (cf. Figure 1) is to follow a consistent and conclusive proceeding starting from precise requirements towards the product that are based on e.g. market potential, costumer needs, laws or new technologies. Resulting from these requirements, product characteristics are mapped via product systems and functions onto elements of the central product structure model. Based on this model, the variants of the product are planned by designing component-variants for each component, allowing for consistent variants management, on from the very beginning of a product project. Technical concepts impact on the design of the product structure model, integrating engineering in this predominant architecture business.

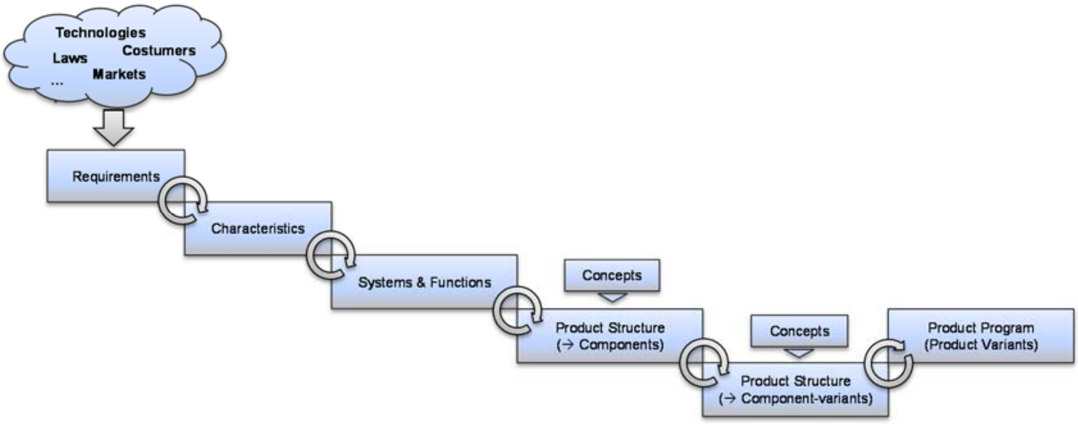

Figure 1. The basic proceeding

Following this procedure a product structure model becomes the essential hub in engineering design phases. The approach is explained in the following in a reference model and in an application in the commercial vehicle industry.
The early phases of product development processes and therein the generic use of a central product structure model is the focus of this paper. Therefore all “artifacts” (e.g. structures, objects, documents, elements etc.) are regarded equally and represented by an artifact symbol following the Business Process Modeling Notation (BPMN) in order to show the basic application and operation of a central product structure in the process. This reference model describes the application of a product structure model containing three levels:

- A **portfolio management layer** that describes the high-level product portfolio by overall product characteristics.
- A **component layer** that breaks down products to single components. At the lowest level of this layer, the variants of each component are arranged, allowing the management of the company’s complete product portfolio in one overall product structure model.
- A **solution element layer** containing concepts, and during realization phase parts and assemblies as the CAD-equivalent of component-variants. Solution elements are the work result of design and validation to the demands made by architecture via components and their variants.

3.1 The reference model

This reference model shows artefacts of these three layers and their role in the process. Additionally, the model contains overall artefacts as a fourth kind that cannot be clearly attributed to one of the three layers. These four kinds of artefacts as objects of the product structure model are sufficient to facilitate engineering design processes, as explained in the following.
The approach focuses on three initial phases of overall product development processes:

- The **definition phase** starting with the initial product idea and ending with release of requirement specifications, containing product characteristics and combinatorics.

- The **architecture phase** containing the development of a specific component layer while mapping product requirements via a product structure down to single component-variants, the most detailed elements of the component layer. The component-variants contain the product specification as an order for the subsequent realisation phase. The results of this phase are technical concepts for each component variant.
- The **realization phase** in which the product specifications and concepts are "realized", i.e. the parts and assemblies are designed and validated. Subsequently, the virtual product is set up in assemblies. The virtual product is the milestone concluding this phase that is followed by the production run, which is not regarded here.

Figure 2 shows the reference model and the four kinds of artefacts (lines in the matrix) being set up and further developed throughout the three phases (rows in the matrix). During the essential architecture phase an exemplary detail of a product structure is shown.

In the initial **definition phase**, market and product requirements are defined in the requirement specification. Furthermore systems (e.g. "braking system") and functions (e.g. "decelerate vehicle") of the planned product are specified as well as criteria for relevant product characteristics (e.g. wheelbase). As this approach aims primarily at making variant management consistent from the beginning on, the design of a structure of characteristics is of major importance. The release of the requirement specification as the result of this initial phase is the qualification to reach the first milestone.

Based on the requirement specification, in the **architecture phase** a specific product structure is designed. This specific product structure is a further development and a subset of a generic, maximum structure containing each possible component of the overall product portfolio (cf. second row in Figure 2). Therefore, already existing solutions in the company are automatically considered in new projects. At the most detailed level of the structure, each component has at least one variant (cf. detail in Figure 2). Product architecture creates variants for each component by transferring product characteristics specified in the definition phase and additional technical characteristics causing restrictions to each variant. This designed and specific (i.e. for a certain vehicle type or series) product structure is further detailed in concept structures generating concepts to realize the specified product requirements. This way, engineering takes part in the design of the product structure in order to impede iterations in the later procedure of the process. Parallel to the design of the concept structure, the product requirements are further devolved and enriched with technical characteristics in order to particularize the component-variants of the concept structure. Hence, component-variants are distinguishable by precise selection rules. Following this procedure of precisely mapping requirements via characteristics to entities of the product structure, the approach achieves consistency in the design process.

By developing concept solutions, first elements of the solution layer (cf. fourth row in figure 2) are designed to visualize the concept structures for the first time. In the automotive industry, the styling of surfaces is a common example for the visualization of concepts. In addition, a package model is set up to analyse the size the design.

To summarize, the major resulting artefacts of the architecture phase at the interface to subsequent realization are a product specification on the basis of a released concept structure and first solution elements like package models. The product structure contains components and their variants of the later product specified by characteristics. These characteristics include the product specification as well as additional technical characteristics. The component-variants and linked technical concepts are the "carrier" of precise product specification and therefore the work assignments for the subsequent design in the realization-phase.

Figure two depicts an exemplary detail of a product structure. The interior is therein broken down into "central column", "dashboard", "steering" and other sections or component-groups. The steering consists of the two components "steering column" and "steering wheel". For the steering wheel in this vehicle project, product architecture plans due to market and product requirements four component variants that are specified by the two characteristics functionality (multifunction or standard) and diameter (large or small).

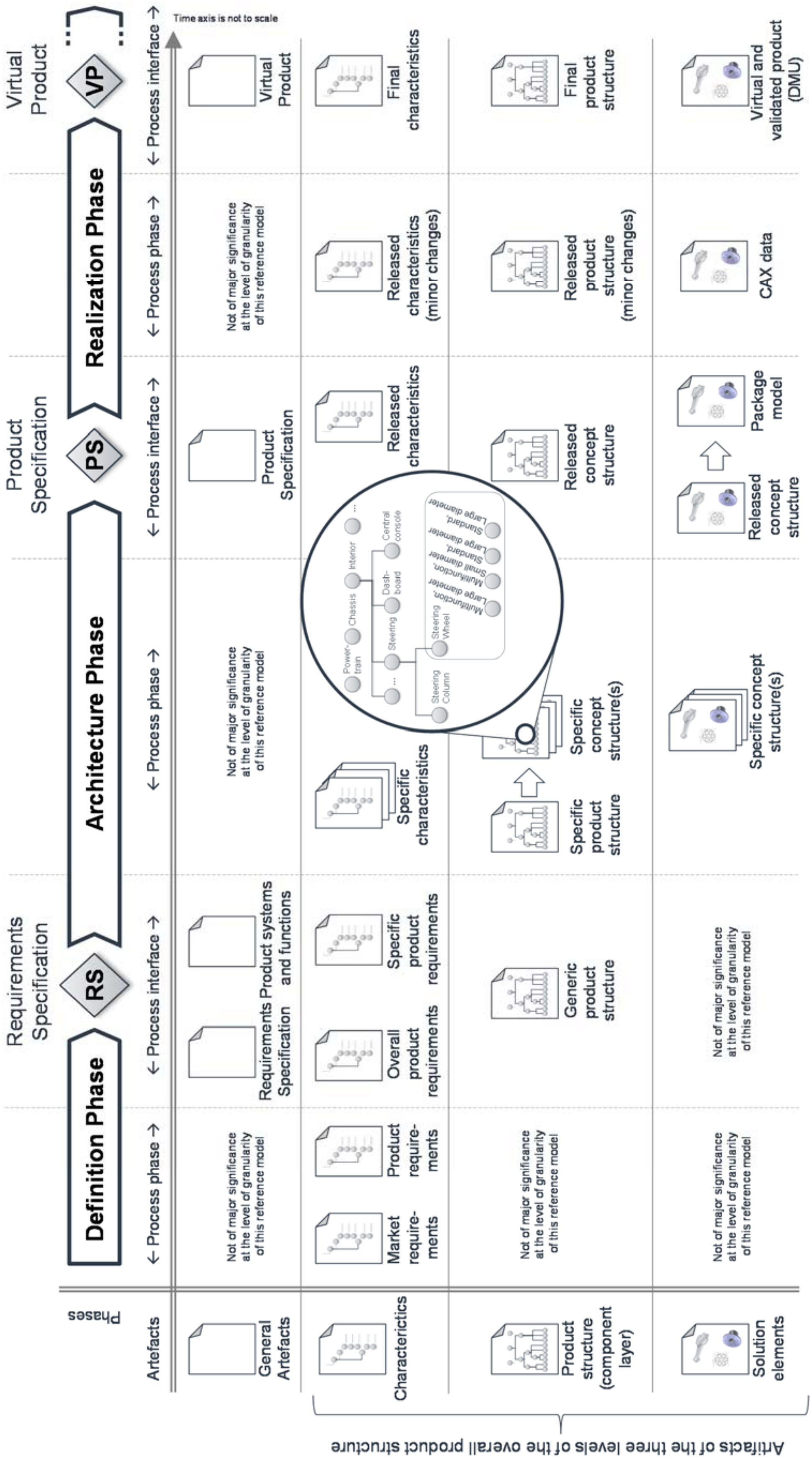

Figure 2. Reference model for product structure management

In the following **realization phase**, solution elements are designed as the equivalent to component variants that are assigned tasks by the architecture department. Following the example in figure 2, four steering wheels have to be realized. However, technical restrictions completing the third layer of the product structure becoming apart in this phase can cause changes to the related subset of the component layer are controlled by a specific, product-structure oriented change and release management, which is not in focus here. As engineering took part in the design of the central layer "product structure", such restrictions cannot occur to a problematic extent causing major changes. The designed CAD-models are tested and verified, generating CAE-data (cf. Figure 2). After integrating verified assemblies and physical testing, a virtual and validated product (digital mock up) is the result of this phase. According to concurrent engineering principles, production preparation takes part in the architecture and realization phase to impede problems in production.

As previously explained, this paper focuses on a product structure as the backbone in particular for early engineering design processes to the point of a virtual and validated product (DMU) as an intermediate result.

3.2 Industrial case study: Application of the reference process

The reference model described in the previous chapter is applied to a commercial vehicle manufacturer's product development process in order to define a possible new target development process that is based on a central product structure. In the application of the reference model has been detailed and set up following BPMN.

In the resulting process chart, swim lanes represent organizational units, such as Product Management, Controlling, Requirements Management, Product Architecture, R&D, Design, Package, Simulation, Innovations Management, Sales, Bill of Materials, Testing, Purchase and Production Preparation. The variety of swim lanes in the process (which are participating roles or stakeholders) already underlines the impact of a product-structure as the backbone for the development process. Every role (and accordingly every organizational unit) involved in early engineering phases participates in this process, employing the product structure as a process integrator.

Product Architecture designs and is responsible for the component layer of the three-layered product structure in new vehicle projects. As previously explained, at the most detailed level of the product structure, component-variants carry relevant and broken down product requirements that are the assignment for subsequent realization. Accordingly, in the application of the reference model the organizational unit Product Architecture has the key role as a connector in this target process, being involved in every section. The concept of component-variants (distinguishable by precise selection rules) that "fulfill" a component in different usages or configurations, optimizes development processes especially in the multi-variant commercial-vehicle branch: This way, vehicle variants can be planned efficiently and consistently in a pivotal architecture phase. The procedure delivers a variety of advantages in order to make early engineering design processes more efficient and to set the condition for efficient development and production phases, as defined component-variants are the means to realize strategies like target costing or target weighing.

Figure 3 shows the process map as an application of the reference model, at an aggregated level that has been overlaid due to nondisclosure reasons. The essential areas of the map are highlighted guiding the proceeding from the very early product idea and project initiation to the release of the virtual vehicle. According to the reference model, subsequent phases are not regarded here.

Starting with a first release to pursue a product or optimization idea, the project is initiated. The specification of product and market requirements leads to the first cross-unit release of the requirements specification, documented in structures of product characteristics. Based on the requirements specification and a generic product structure, product architecture creates a specific product structure for planned vehicle types mapping characteristics via systems and functions to components and subsequently to component-variants.

The detail in Figure 3 shows the artifacts' product specification and the generic product structure as inputs to the graduated design of a specific vehicle structure. In this phase of the design process, product architecture manages development, selection and integration of conceptual solutions. The product specification is subsequently documented in the released product structure. Based on the

product specification, the overlapping sections design, simulation, and validation take place. Finally, vehicle integration and the release of the virtual vehicle complete the realization phase – managed by the architecture unit again.
The process shows the architecture unit as responsible for the component layer of the product structure model that works as a backbone throughout the vehicle development process. The existence of a product architecture unit that bridges the gap between requirements management and realization while integrating engineering is the precondition for the introduction of a development process based on a central product structure.

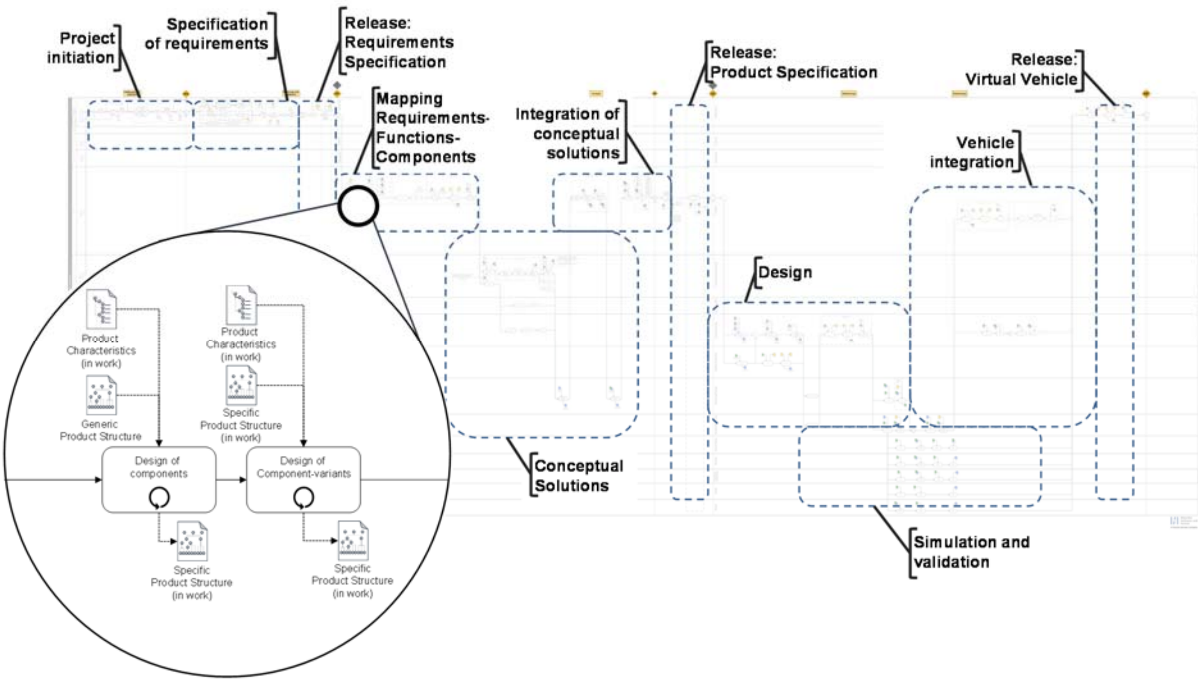

Figure 3. Application of the reference model (commercial vehicle industry)

4. Discussion

As previously explained, the results reflect the current status of the study. Further details can be observed when the implementation is concluded and real-life processes were performed with the system.
The application of the approach at a commercial vehicle manufacturer showed so far that management of a central product structure model promises to deliver possibilities to optimize product development. The following, primary effects are expected from an implementation of the concept introduced in this paper. These primary effects can be separated into improvements concerning the organizational dimension in development processes or projects, as well as improvements in respect of the temporal dimension.
Concerning the **temporal dimension**, product structure management allows for continuity and frontloading:
The core of our product structure management is the interaction between a component layer and a solution element layer. Therein, the development of concept solutions is guided by specified component-variants. Architecture as an organizational unit plans the variability of the product programme before realization starts, allowing for consistent variant planning from the very beginning on. Therefore, concept elements reach a higher level of maturity earlier in the process. Accordingly, the product structure model enables an overall **frontloading** in development processes and hence, causes advantages like e.g cost saving. The release of the product specification (based on the product structure) integrates all stakeholders of the development process, minimizing iterations in the process.

During realization, component variants and correlating solution elements are precise objects for efficient engineering change and release management (ECRM).
Product and market requirements are transferred precisely via systems and functions to single components and their variants. A product structure developed in a traceable way carries all relevant information from the early requirement stage to realization. All relevant data created and further developed in the process are associated to the elements of the product structure model. Thereby, the product structure model enables continuity in a development project.
Regarding an **organizational dimension**, product structure management effects integration and transparency in development projects:
A generic product structure sets the baseline for each product project. The design of the framework facilitates product specific detailing and further-development of the generic product structure. The design of the three-levelled product structure model provides a clear procedure for the initial three phases of product development, defining the contributions of roles and organizational units in the process. The reference model allows for the deduction of synchronization points and serves therefore as a backbone for development processes. This way, the product structure is kept up to date by all stakeholders and thereby enables the integration of their work. The product structure as a common database makes all existing solutions accessible and consequently reusable allowing for common parts and module management across the product portfolio by pre-designating common interfaces.
In the product structure model, all product data is kept up to date and is accessible for all stakeholders. This way, the model becomes the central platform of efficient communication in the project, creating overall transparency. A lack of transparency is regarded a major source for rising product and process complexity. The model itself reduces unnecessary product complexity. Establishing a reference process in combination with the product structure model creates process transparency and reduces process complexity. Therefore, the approach enables large-scale projects, e.g. modularisation of product portfolios. Accordingly, the product structure management delivers starting points for an overall reduction of complexity.
The described primary effects of product structure management are depicted in Figure 4:

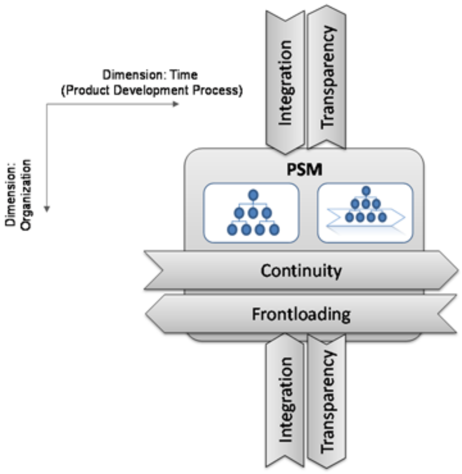

Figure 4. Primary effects of the introduced concept

Furthermore, product structure management allows for **lean process management** in development phases by giving a comprehensive view over the product portfolio as well as over existing technologies in companies. The central product structure serves a consistent data basis enables transparency over existing solution in the company. In new projects it helps to identify necessary new developments of components and impedes overhead expenses. The approach makes lean decision making possible, as decisions are based on a central product structure.
The application in the industry identified the product structure model and the reference process as the **basis for the implementation** of a PDM system, as it predetermines e.g. roles and responsibilities, processes and use cases.

However, there are certain limitations to the issue. The case study revealed that there is significant effort required to introduce Product Structure Management in enterprises, as firstly the **thinking in new structures** means changes to the common mindset, which is a challenging issue, as we learned in the industrial case study. Furthermore the assignment and redistribution of responsibilities following the product structure means changes to established procedures. Also, there is considerable **effort** in maintaining and keeping the structure up to date.

We conducted our case study at a major commercial vehicle manufacturer, developing highly variant products. We assume that a certain product complexity and a certain size of enterprise are necessary to derive significant optimization following our suggestions.

5. Conclusion and further work

Our procedure suggests Product Structure Management as the backbone for engineering design processes. Therein, a three-layered product structure model is further developed in development projects.

Product Structure Management has to be considered as a procedure to gain transparency and to consistently realize well-established approaches like product modularization.

We consider the concept of Product Structure Management as adaptable to enterprises with a similar product portfolio, e.g. car manufacturing. Short term observations of benefits and limitations were discussed in the project.

In addition, long term impacts on the development process could not be observed yet. This will be part of further collaborative industrial and research work.

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