MECHATRONIC MODULARIZATION OF INTELLIGENT TECHNICAL SYSTEMS

Lipsmeier, Andre; Westermann, Thorsten; Anacker, Harald; Dumitrescu, Roman
Fraunhofer Institute for Mechatronic Systems Design IEM, Germany

Abstract

A successful transformation of mechanical engineering products toward Intelligent Technical Systems (ITS) requires an interdisciplinary and modular system architecture as well as an interdisciplinary understanding of the system for all stakeholders. Different approaches for the development of modular product structures as well as for generating interdisciplinary understanding of the system for all stakeholders exist. There is, however, a lack of a method which is consistent with the approach of Model-Based Systems Engineering (MBSE) and takes the aspects of all the disciplines involved in the ITS context into account.This contribution shows an approach for improving the development processes of Intelligent Technical Systems with modularization combined with MBSE. The approach is divided into five phases: Target Definition (Phase 1), System Modelling (Phase 2), System Analysis (Phase 3), Identification of mechatronic Modules (Phase 4) and Restructuring of mechatronic Modules (Phase 5). In addition, the results are validated by an industrial separator. The results clarify the benefits of modularization combined with MBSE to improve the development processes of ITS.

Keywords: Product architecture, Product structuring, Systems Engineering (SE)

Contact:
Andre Lipsmeier
Fraunhofer Institute for Mechatronic Systems Design IEM
IEM
Germany
andre.lipsmeier@iem.fraunhofer.de

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1 INTRODUCTION

Today's mechanical engineering products are characterized by the close interplay of mechanics, electronics, control engineering and software engineering. This interaction is commonly referred to as mechatronics (Gausemeier et al., 2011). The development of information technology opens up fascinating perspectives that have the potential to go far beyond current standards. The result are Intelligent Technical Systems (ITS) which are mechatronic systems with inherent partial intelligence (Dumitrescu, 2010). The usage of ITS within production systems enables Smart Factories with reconfigurable and adaptable production. The keyword "Industrie 4.0" stands for the fourth industrial revolution which describes the radical change of production engineering. The interconnection of machines, manufacturing equipment, work pieces as well as transportation systems through the internet allows decentralized coordination and demand specific reconfiguration of the production (Kagermann et al., 2013). This radical change of production engineering affects both lead market and lead providers. With regard to lead providers, the mechanical engineering industry is particularly affected by the further development of mechatronic systems toward ITS. Compared to products of the automotive and electrical equipment industries, products of the mechanical engineering industry are highly customized. High product complexity and low quantities result in a high variant diversity which requires additional efforts from product engineering and manufacturing. Increasing costs and a long time-to-market are related to these effects. To meet the rising efforts caused by a high variant diversity, the product structure plays an essential role. The product structure describes the structured composition of components that make up the final product (Schuh, 2005). Along with the functional structure, the product structure is one of the building blocks of a product architecture. Through the structuring of products, positive effects can be achieved on different levels. Benefits for the development and production as well as for the use and recycling of the product are generated by using a suitable product structure. An appropriate approach for structuring products is Modularization. With Modularization, systems are subdivided into functionally and physically independent modules. Modules and standardized interfaces enable the reuse of components in different customized products with varying functions. Due to the increasing incorporation of information and communications technology (ICT) into ITS, more and more functions are being implemented through software. Focusing only on the mechanical or mechatronic product structure does not suffice for a modularization of ITS. Against this background, the modularization of ITS requires new cross-disciplinary approaches. For a cross-disciplinary approach it is necessary to abstract the real, complex system of ITS by using a system model to identify relations between components and generate transparency. Promising approaches for the interdisciplinary description of technical systems are Systems Engineering (SE) and Model-Based Systems Engineering (MBSE). SE is an interdisciplinary approach for the successful realization of more or less complex systems (INCOSE, 2010). By creating transparency through an interdisciplinary understanding of the system, the increasing complexity of technical systems can be managed. MBSE focusses on a system model which allows a holistic view on the system. Abstracting the real system into an abstract system model helps to create a common understanding of the system. Furthermore, the system model is a platform for communicating and tracing requirements throughout the entire product lifecycle (INCOSE, 2007). The close interplay of Modularization and MBSE have the ability to support product engineering within the mechanical engineering industry which can be boiled down to two specific goals: support the product engineering in terms of modular system architecture design; improve the communication inside the company and with customers. This contribution presents an approach on how to support the engineering of ITS in terms of modular system architecture design with Modularization and Model-Based Systems Engineering. In section two, we will explain the initial situation and our field of action in the context of Modularization, modular system architecture design and Model-Based Systems Engineering. Subsequently, we will describe the concepts of Modularization and Model-Based Systems Engineering. In section four the approach will be explained in detail. Our approach will be evaluated using the example of an industrial separator. We will sum up the major points and give a short outlook on our future work in the last section.

2 INITIAL SITUATION AND FIELD OF ACTION

The mechanical engineering industry with products like machine tools, food processing or packaging machines faces two major challenges: market pull with customers who require highly customized products and a short time-to market as well as the technology push with new technologies. Mechanical engineering products are based on a close interaction of mechanics, electrics/electronics, control engineering, software engineering and new materials (Dumitrescu et al., 2013). The development of information technology is the key driver for the transformation of mechatronic systems toward Intelligent Technical Systems (ITS). ITS are mechatronic systems with inherent partial intelligence and can be characterized by four major aspects: adaptivity, robustness, predictiveness and usability (Adelt et al. 2009). Various fields like mobility, buildings, healthcare and industry will be permeated by ITS in the near future. In the past, mechanical engineering products were characterized by mostly relying on mechanical components. Nowadays, however, these products are based on a close interaction of various disciplines. This will entail a rising complexity of technical systems and their development. In addition to an increased complexity, a higher variant diversity as well as customized systems have to be handled in the development of ITS. In order to understand, develop, modify or shape complex systems like ITS, the generation of transparency throughout the system is an elementary step. The depiction of interrelations of components in the overall system and thus the complexity of a system can be represented by the product structure. The product structure is an integral part of the product architecture, along with the function structure. The product architecture describes in generic terms which functions are fulfilled by which components (Ulrich, 1995). Functions are defined from the viewpoint of the customer and the markets, while the product structure represents the manufacturer perspective (Ulrich, 1995). The product structure can be thought of as the structured composition of components that form the final product (Pahl et al., 2012). In the context of ITS, a suitable product structure is required for a plug and produce capability. A suitable product structure supports the identification and adaption of dependencies and interfaces of modules and components, which is the basis for a plug and produce capability. According to SCHUH, the most widespread categories of product structures are: type series, packages, construction kits and modules (Schuh, 2005). Those categories are shown in Figure 1.

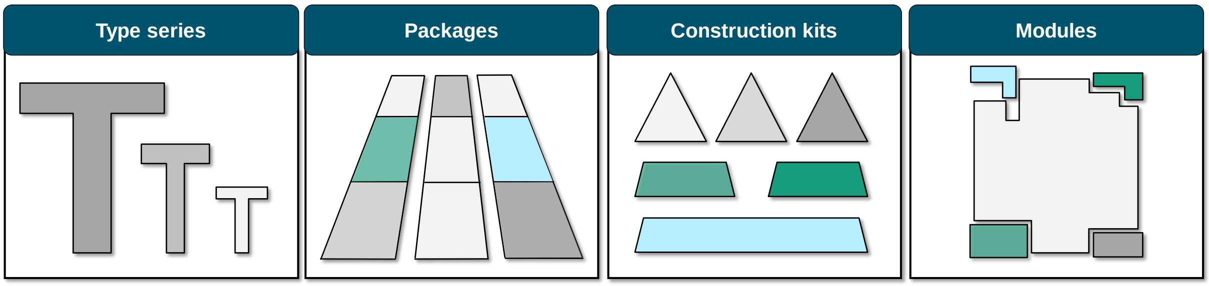

Figure 1. Categories of product structure according to Schuh (2005)

According to Pahl (2007), type series can be defined as a technical construct which is using the same technical solution and manufacturing scheme to fulfil the same function in different size fractions for a wide application area (Pahl et al., 2007; Meyer et al., 1997). Albers defines type series as having a similar product architecture, whose dimensions can be varied by scaling of certain parameters (Albers, 2015). Packages contain components with different functions, which can only be combined into one defined package, not into other packages of a product family. Type series and packages are only partial aspects for the structuring of products (Schuh, 2005). These are neglected in the following. Construction kits subdivide the system into function-depending units. These function-depending units can be combined individually and include one or more different functions each (Baumgart, 2005). According to Koller (1994), a construction kit consists of components of identical or differing functionality and build for fulfilling different functionalities through combining of components (Koller, 1994; Borowski, 1961). Albers proposes that construction kits are abstract constructs which contain all subsystems for a configuration of various systems by using rules for the dictation of the product subsystems architecture (Albers, 2015). Regarding the modular design, a system consists of modules. Modules are attaching parts with uniform interfaces (Rathnow, 1993). According to Lindemann and Maurer (2006), a module designates functional and logical units that are interchangeable (Lindemann and Maurer, 2006). Through modularization, the overall system is subdivided in modules that are functionally and physically independent (Renner, 2007; Schmidt, 2002). This functional independence results in a dependence of single modules with one function each (Baumgart, 2005). Another characteristic feature of modules is the very few numbers of interfaces (Koppenhagen, 2004; Blees, 2011; Wallentowitz et al., 2009). For the exchangeability of modules, clearly defined and unified interfaces are required. Through combining different modules, a high volume of variants and functions can be realized with only minimal adaption effort. Consequently, modularization addresses the challenges of highly customized products with a high variant diversity (Rapp, 1999). The aim of modularization is to increase the product diversity via standardization of components and interfaces while reducing manufacturing efforts (Schuh, 2005). It enables an allocation of the complexity into independent modules, the improvement of physical and functional interfaces and an enhancement of flexibility. Regarding the development of ITS, these aims are highly significant. ITS enable a number of novel features, services, and functions. The essential enabler for the possibility of the function extension is the integration of software (Kagermann et al., 2013). Due to the shift of emphasis from mechatronic components to software components, existing approaches on modularization are not applicable. Modularization of ITS must place the focus on the close interplay of mechanical and electronic components and, in particular, on the software. In this context, the use of a holistic view on the system can support the modularization of ITS. A suitable approach for using a holistic view on a system is Systems Engineering (SE). SE includes systems thinking, discipline specific engineering approaches (methods, tools and procedure models), management aspects and human sciences (Haberfellner et al., 2012). The concept of Systems Engineering encompasses a holistic consideration of a system in order to strengthen the understanding of the system and to efficiently solve a complex development task. Model-Based Systems Engineering (MBSE) contributes to this idea. It addresses a holistic description and analysis of a system based on models beginning in the early phases of the product development throughout the whole product lifecycle. SE and MBSE with modelling languages like SysML or CONSENS have the ability to support the interdisciplinary system architecture design.

Regarding the development of Intelligent Technical Systems, the following challenges need to be put into focus: **interdisciplinary and modular system architecture design as well as reusable modules; interdisciplinary understanding of the system for all stakeholders;** The modular system architecture is an important aspect for the successful transformation of mechanical engineering products toward ITS. The development of modular architecture concepts with modularization and Systems Engineering will be the focus of the next chapter.

3 STATE OF THE ART

A successful transformation of mechanical engineering products toward ITS required an interdisciplinary and modular system architecture as well as an interdisciplinary understanding of the system for all stakeholders. Regarding the modular system architecture, many methods in literature address the use of construction kits, e.g. Function-oriented Construction Kits (Renner, 2007), Development of Product Construction Kits (Schuh et al., 2010), Construction Kit Development suitable for Production (Rudolf, 2013), Complexity oriented Development of Construction Kits (Arnoscht, 2013). Many further methods for modularizing exist, e.g. Modular Function Deployment (Franke et al., 2002), Modular Design Method (Stone, 1997), Modular Product Development (Göpfert, 1998), Integrated Development of Modular Product Families (Krause et al., 2014) or Method for Developing Modular Product-Families (Blees, 2011). Pimmler/Eppinger show a method for modularization of existing systems with design structure matrices (DSM) (Pimmler et al., 1994). The approach of DSM goes back to Steward who introduced it for handling iterations within development processes. A binary matrix describes the dependencies between tasks. Through partitioning the matrix, strong dependencies can be identified and the process can be revised accordingly (Steward, 1981). The approach of Steward has been adopted by many other authors for different purposes but with the common goal of reducing complexity. Examples are process planning (Eppinger et al., 1994; Carrascosa et al., 1998), project management (Danilovic, 2007), variant management (Bongulielmi, 2001), and the modularization of products (Browning, 2001), (Steffen, 2007). Lindemann et al. (2009) establish the multi domain matrix to merge the different approaches (Lindemann et al., 2009). A special case of modularization is the platform design, which aims at an application of standardized components in the form of a version-neutral platform and product specific extensions (Haf, 2001). Many authors describe the platform as an interface carrier or as a set of systems and interfaces which build a common structure (Meyer, 1997; Blees, 2011). The platform is used as a basis for numerous variations which is decoupled from the product-life-time of single products/ variants. Roth provides an approach to the development of a platform concept, which is a standardization concept for small-scale machine engineering (Roth et al., 2014). In this approach, the platform contains all elementary and invariable components as basic-

modules. Adaption-modules and variation-modules were attached to the basic-modules, whereby the product can be customized. While adaption-modules are standardized, variation-modules are individually developed for each application (Roth et al., 2014). In our approach, we adapt this standardization concept for building new mechatronic modules. For improving the architecture of an existing system, a common understanding of the system for all stakeholders is necessary. The approaches of Systems Engineering and Model-Based Systems Engineering are suitable to gain an interdisciplinary understanding of the system for all stakeholders. This is the main fundament for the development of modular system architectures. By focusing on a system model, Model-Based Systems Engineering allows a holistic, domain-spanning perspective on the system. The system model constitutes the basis for communication and cooperation. The description of the system aspects through the use of suitable diagrams helps to increase the overall transparency. A method (e.g. SysMod (Weilkiens, 2014) or CONSENS (Kaiser et al., 2013)) in combination with a modelling language (e.g. SysML (Alt, 2012; Weilkiens, 2014)) define what aspects have to be considered and in what diagrams are to be used for the description. The active structure is one of the main aspects of nearly all MBSE-approaches. It describes all system elements (Software and Hardware) and their relationships (e.g. mechanical connection or information flow). In our approach, we use the method and modelling language CONSENS to describe the system in a domain-spanning way.
In summary, different approaches for the development of modular product structures as well as for generating interdisciplinary understanding of the system for all stakeholders exist. There is, however, a lack of a method which is consistent with the model-based approach in the design and takes the aspects of all the disciplines involved in the ITS context into account.

4 METHOD FOR MECHATRONIC MODULARIZATION OF INTELLIGENT TECHNICAL SYSTEMS

4.1 Example

To explain our results in this section, we will use the example of a separator. A centrifugal separator separates substances and solids from liquids or separates liquid mixtures at the same time as removing solids. The function relies on centrifugal forces and differing inertia of the raw product. Due to a wide range of possible applications, a high number of separator types exist: solid-wall separators, chamber separators, self-cleaning disk separators etc. Separators are used in a wide range of industries including beverage production (e.g. breweries), chemical, dairy, energy, environmental, marine, oil, gas and many more. The high number of possible applications results in a high number of different separator types and variants. Separators have an integral product architecture with a complex mapping from functional elements to physical components. A change of the mechanical structure implies a high cost of change due to this high integrity. Our approach is divided into five phases (see Figure 2).

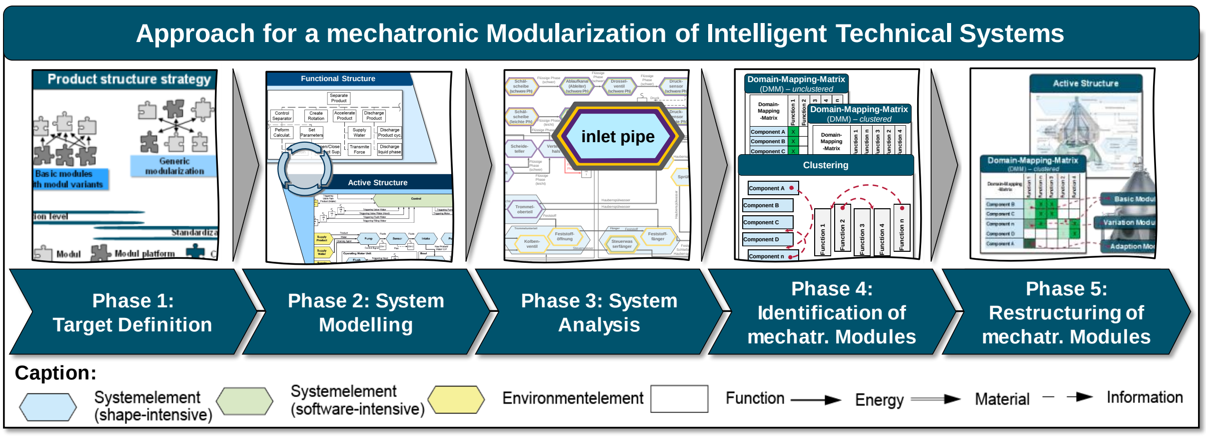

Figure 2. Overview of the approach

Phase 1 - Target definition: Defining a target of modularization is the first step of the approach. In this phase, the target markets as well as technologies and module drivers have to be determined. Examples for module drivers are: optimization for assembly or optimization on functionality. It is important to involve experts from various departments like Marketing, Sales, Development, Construction and

Production for defining a target. The product structure and shape of modules depend on the module drivers which define criteria for the modularization. This includes defining requirements for the degree of expression of standardization and individualization as well as for the product family crossing. The result of this phase is the definition of a product structure strategy, which defines the goal and thus the application and the benefit of modularization (see Figure 3).

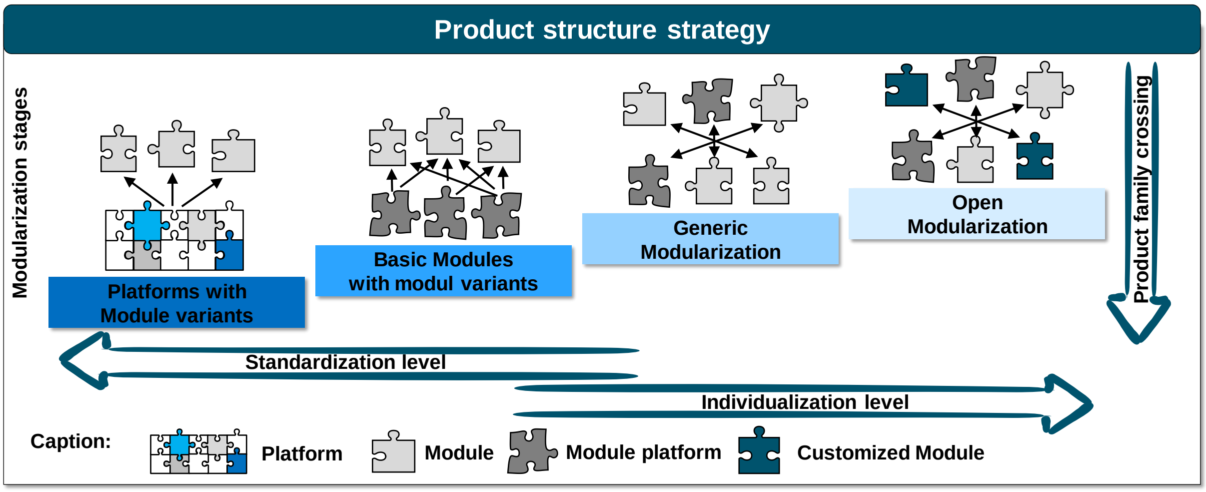

Figure 3. Product structure strategy (Schuh, 2005)

In this respect, it is necessary to answer the overarching question which market requirements exist for the product and what kind of product variants will be worthwhile in the future. Regarding the example of the separator, the first step was a target definition in an interdisciplinary workshop. The following target of modularization was established: Using mechatronic modules for the plug and produce capability of separators. This target addresses the increasing efforts for the software development and customization for individual configured separators. Through the pursuit of this target, a significant step for the further development toward ITS is made possible. In addition, it was necessary to define a suitable product structure which would enable a plug and produce capability of mechatronic components without significantly increasing the development and manufacturing efforts. Using a platform with module variances was defined as the product structure strategy.

Phase 2 - System Modelling: In the second phase of the approach the system is modelled. In the course of interdisciplinary workshops, a domain-spanning description of the system is created. In this context, the focus has to be on a system creation in a domain-spanning way by experts of various departments (e.g. mechanical engineering, software engineering, sales department etc.). A domain-spanning description of the system means to describe mechanical parts of the system as well as software parts in equal measure. Therefore, the method and modelling language CONSENS can be used. CONSENS allows a domain-uncommitted description which cannot be created only with CAD drawings or wiring diagrams. The domain-spanning description considers all system elements, environment elements and their interrelations. In the case of an existing systems model, the task is to transform the model into an active structure of CONSENS. Depending on the circumstances, the model might need to be corrected or extended depending on its availability. In the case that there is no systems model for the considered system available, it has to be created from scratch. Regardless of the different cases, there are four relation types to classify the relations between the elements within the active structure: material flow, energy flow, signal flow, and mechanical linkage. By working with the systems model, different views and opinions become apparent. The discussion between developers of different disciplines leads to a common understanding of the system and a mechatronic view in the form of an active structure. Along with the active structure of the system, a functional structure is created during the system modelling phase. The combination of partial functions to fulfil the overall function is called functional structure (Kaiser et al., 2013). The overall function of a system (e.g. “separate product”) can be divided into partial functions with a lower complexity (e.g. “create rotation” and “accelerate product”). For the domain-spanning description of the separator example, the method and modelling language CONSENS was used. The created domain-spanning description includes elements of hardware and software, environment elements as well as their interrelations. Figure 4 illustrates the activities of the second phase by means of the separator. The description of the system was created by involving various disciplines like mechanical engineering, software engineering and electric goods department as well as process engineering. Through interdisciplinary workshops, a common understanding of the system was created. The environment of the separator as well as the active structure was modelled. An essential part of the active structure is the domain-uncommitted description of the software. In addition, the functional structure was created for analysing system function from the market and customer perspective.

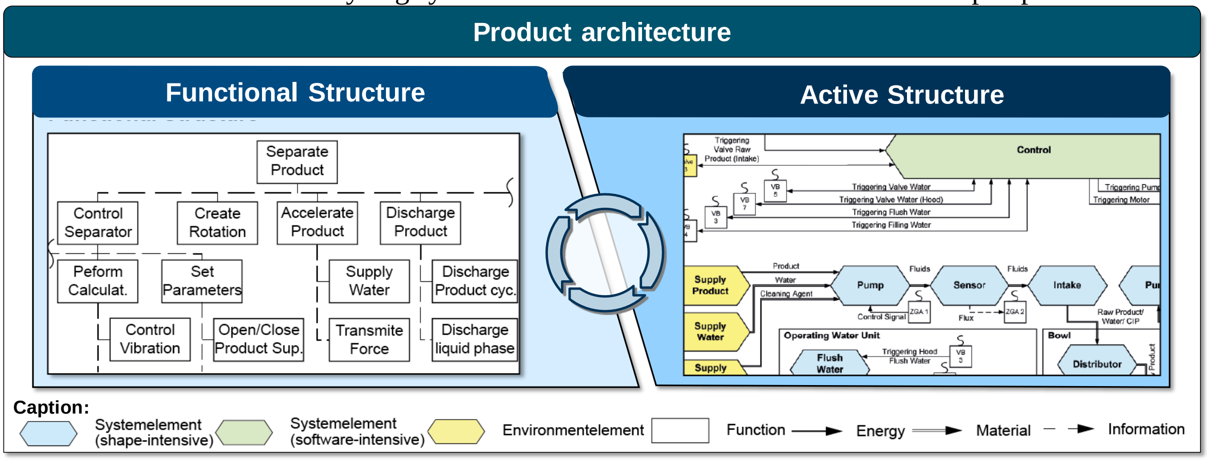

Figure 4. Product architecture

Phase 3 – System Analysis: Analysing the system is the task of the third phase. For analysing the system, it is important to analyse the existing structure of the software and electric equipment. The main task is to identify internal connections of the system as well as existing variants. An approach for identifying the internal connections is building and analysing Design-Structure-Matrices (DSM) as well as Domain-Mapping-Matrices (DMM). For identifying dependencies of different components (product structure), the DSM can be used. DMMs can be used in product development to demonstrate dependencies of functions and components (product architecture). Regarding the existing variants, the existing product portfolio has to be analysed. Furthermore, it is important to know which elements are mandatory and which are optional. The analysis of variants addresses shape-intensive elements (Hardware) as well as software-intensive elements (Software). While the hardware is often structured into modules, the software is often not appropriately structured. In the current example, all variants of the product portfolio as well as the structure of mechanics, electric and software were analysed. Using variance and application matrices, it is possible to show variants of the mechanical parts (e.g. hood) and electrical parts (e.g. pressure sensor), which are both shape-intensive elements, as well as existing software. Variance-depending components were labelled in the active structure (see Figure 5).

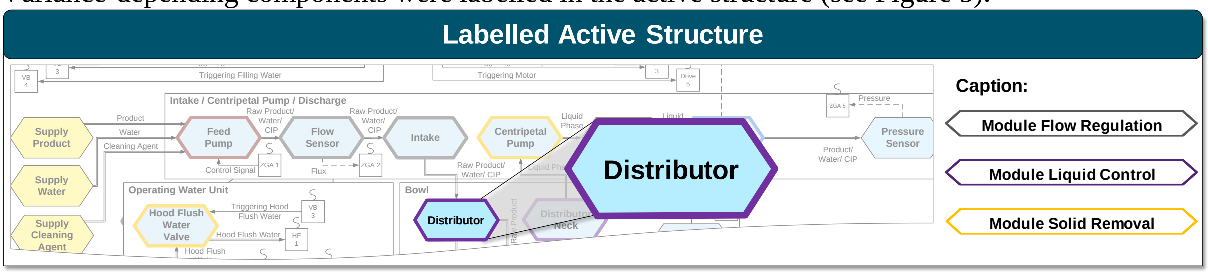

Figure 5. Labelled active structure

For analysing the dependencies of mechanical, electrical and software components Design-Structure-Matrices (DSM) were elaborated. Domain-Mapping-Matrices (DMM) were worked out for analysing the relations between components and functions. Thereby, an analysis of the control structure is made possible. With regards to the example, the software does not have a sorted architecture. Consequently, new variants generate high efforts because the software code has to be changed manually.

Phase 4 - Identification of mechatronic modules: The focus of the fourth phase is the identification of existing mechatronics modules. For this, the previously elaborated DMM has to be clustered. Elements of the DMM are clustered into chunks, which involves moving rows and columns in a descending manner (see Figure 6). It has to be decided into how many clusters the matrix should be modularized.

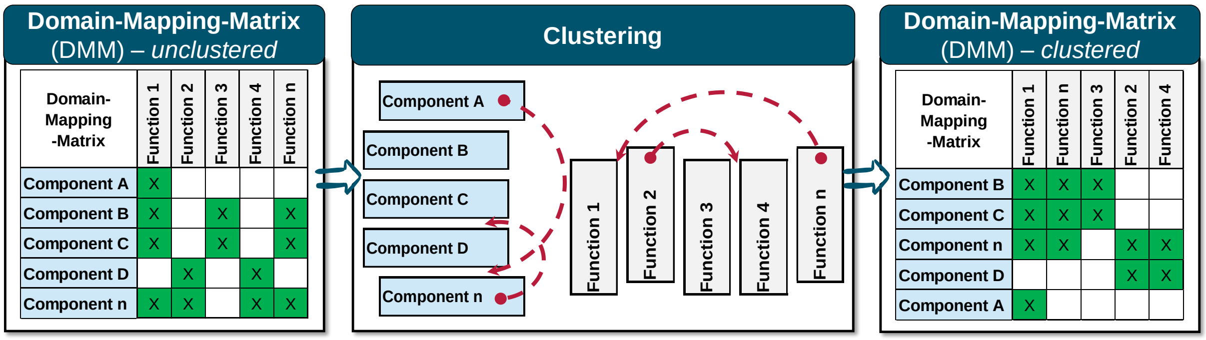

Figure 6. Clustering of the DMM

The most qualified quantity of clusters needs to be determined by testing. With the clustering of the DMM, the most similar pairs of relations between functions and components are shown. In the context of clustering, only components which are dependent on the product variant have to be considered. As a result of the clustering, existing dependencies and modules of the product architecture can be identified. Regarding the example of the separator, the purely mechanical construction of the separator is neglected. Modularization focuses on the software components and the electronic components required for plug and produce capability. As a result, the DMM only consisted of functions which are carried out by software and electronic components. For the identification of existing mechatronic modules, the DMM as well as the DSM were clustered. On the basis of the clustered DMM, modules could be created, which have a large set of components for the fulfilment of different functions. The dependencies and interfaces of the components among each other were examined on the basis of the DSM. For the clustering of the matrices, it is useful to work with a software tool. In the example, the software tool iQuavis was used.

Phase 5 - Restructuring of mechatronic modules: Regarding the final phase of the approach, the restructuring of mechatronic modules is addressed. Existing modules which are identified in the previously phase have to be analysed and adjusted in context of the product structure strategy. Doing this, the modules are subdivided in basic modules, adaptation modules as well as variation modules so that the identified modules of a single function can be reused in similar or related functions. Interfaces of restructured Hard- and Software components have to be standardized. Analog to the variance-depending components, module-depending components have to be labelled in the active structure. This creates transparency through a cross-domain documentation and a communication base for the various departments as well as for agreements with the costumer. In the example, the defined product structure strategy was to use a modular Platform with module variances which offers a good agreement between standardization and individualization (see Phase 1). In the final fifth phase, this product structure strategy was implemented by restructuring of existing modules. For this purpose, the previously identified existing modules (see Phase 4) were divided into basic-modules, adaption-modules and variation-modules (see Figure 7).

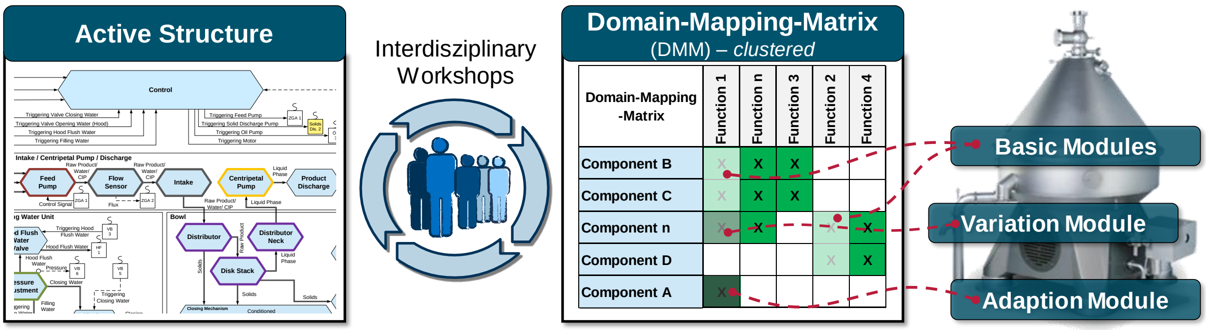

Figure 7. Restructuring of modules

Basic modules contained software and electrical components of the separator for different function-neutral platforms. In order to increase the degree of customization, various basic modules were formed for different applications of the separator. Function-specific extensions were depicted by adaption modules and variation modules. Adaption modules were created for components which could be reused for a small number of functions. On the other hand, variation modules were used for components that had to be customized or developed for individual functions. Along with the restructuring of mechatronic modules, the active structure was use as a communication base for the different domains. Using this approach, the decoupled functions can be transferred to decentralized units, thereby enabling plug and produce capability.

5 CONCLUSION AND OUTLOOK

Highly customized products dominate in the mechanical engineering industry. Typical products like machine tools, food processing or packaging machines are characterized by a high product complexity and low quantities. This generates a high number of variants and leads to high change efforts during the adaption of existing products. Main challenges of the development process of Intelligent Technical Systems are: modular system architecture design; interdisciplinary understanding of the system; communication inside the company and with customers. Therefore, we introduced an approach for improving the development processes of Intelligent Technical Systems with modularization combined with Model-Based Systems Engineering. In addition, we validated our results exemplified by an industrial separator. Our results meet the mentioned challenges as follows: creating a domain-spanning description of the system to gain a common understanding for a sustainable communication within the company and with customers (Phase 2-5); optimizing the system architecture by analysing the existing product structure and defining new mechatronic modules (Phase 3-5). In summary, our results clarify the benefits of modularization combined with MBSE to improve the development processes in the mechanical engineering industry. In future work we will analyse further validation examples in the innovation project "Separator i4.0" which is part of the Leading-Edge Cluster it's OWL (Intelligent Technical Systems OstWestfalenLippe).

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