IMPROVING ORDER FULFILLMENT PROCESSES WITH MBSE

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Abstract

Highly customized products dominate in the mechanical engineering industry. Products like machine tools, food processing or packaging machines are characterized by a high complexity, a low quantity and a long-term machine life. This leads to a high number of variants and project specific modules and components. High efforts during order fulfillment processes occur. The development of mechanical embossed products to Cyber-Physical Systems reinforces the difficulties of the mechanical engineering industry. The interdisciplinary approaches of Systems Engineering and Model-Based Systems Engineering are suitable to improve order fulfillment processes. Therefore we introduce an approach to improve order fulfillment processes with Model-Based Systems Engineering. Our results meet the challenges of the mechanical engineering industry as follows: creating a domain-spanning description of the system and the business process to gain a common understanding; optimizing the system architecture by defining mechatronic modules; improving the sustainable communication within the company and with customers by training courses and tool support. The results are validated by a practical example.

Keywords: Model-Based Systems engineering, Product architecture, Mechatronics, Communication, Mechanical engineering industry

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1 INTRODUCTION

Nowadays, mechanical engineering products are characterized by the close interplay of mechanics, electronics, control engineering and software engineering. This interaction is expressed by the term mechatronics (Mori, 1969; Comeford, 1994). The conceivable development of information technology opens up fascinating perspectives which have the potential to go far beyond current standards. Intelligent Technical Systems, mechatronic systems with inherent partial intelligence, emerge (Dumitrescu, 2010). The term Cyber-Physical Systems (CPS) encompasses Intelligent Technical Systems and their interconnections among themselves during operation. CPS characterize the rising complexity of such technical systems based on the decomposition of information processing in subsystems and the associated necessary combination, coordination and communication between the subsystems; examples are embedded systems. Internet will be the most important platform of communication. However, CPS do not only solve problems in cyber space in a collaborative way, but also have a direct impact on real physical processes by the use of their actuators (Broy, 2010). The usage of CPS 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 over the internet allows decentralized coordination and demand specific reconfiguration of the production (Kagermann et al., 2013).

Compared to products of the vehicle manufacturing and electrical equipment industries, products of the mechanical engineering industry are highly customized. High product complexity and low quantities generate a high number of variants and lead to high change efforts during the order fulfillment processes. The development of mechanical embossed products to Cyber-Physical Systems reinforces the difficulties of order fulfillment in the mechanical engineering industry.

An approach to meet the rising complexity of technical systems and the challenges of the mechanical engineering industry is Systems Engineering (SE). 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. Model-Based Systems Engineering (MBSE) focusses on a system model, which allows a holistic view on the system. Abstracting the real system to an abstract system model helps to create a common understanding of the system. Furthermore, the system model is a platform to communicate and trace requirements throughout the whole product lifecycle (INCOSE, 2007). SE and MBSE have the ability to support the order fulfillment processes within the mechanical engineering industry. That means concretely: support the sales department in terms of order preparation; support the engineering department in terms of modular system architecture design; improve the communication inside the company and with customers.

This contribution shows an approach how to improve order fulfillment processes with Model-Based Systems Engineering. In section two, we will explain the initial situation and our field of action in context of order fulfillment in the mechanical engineering industry. Afterwards we will carry out the concepts of Systems Engineering and Model-Based Systems Engineering. In section 4 the approach will be explained in detail. Our approach will be evaluated over the example of a separator. Eventually we will sum up the major points and give a short outlook on our future work.

2 INITIAL SITUATION AND FIELD OF ACTION

The mechanical engineering industry is one of the biggest industries in Germany (Turnover about 200 bn EUR in 2013). While the vehicle manufacturing and electrical equipment industries are characterized by the production of large series with standardized components, highly customized products dominate in the mechanical engineering industry (Wiechers and Hell-Radke, 2014). Typical products like machine tools, food processing or packaging machines are characterized by a high complexity, a low quantity and a long-term machine life. The low quantity on the one hand and the high complexity on the other hand lead to a high number of variants and project specific modules and components. Customers of the mechanical engineering industry demand a high flexibility and a short time of delivery (Foerster, 2003). Thus, companies of the mechanical engineering industry have to offer highly customized products with a decreasing time-to-market and reduced costs.

To improve order fulfillment processes in the mechanical engineering industry it is necessary to analyse the reasons for the high number of variants and when they occur. An appropriate way is the

customer order decoupling point (CODP). Normally the CODP is defined as the point in the value creation process where customer order driven production and forecast driven production are separated (Giesberts and van den Tang., 1992; Wortmann et al., 1997). Mainly the CODP is a tool used to analyse activities related to production and material flows. In this contribution, the CODP helps to distinguish the situation of the mechanical engineering industry from other industries, e.g. the vehicle manufacturing industry. Typically, four CODPs are defined: engineer-to-order (ETO), make-to-order (MTO), assemble-to-order (ATO) and make-to-stock (MTS) (Wikner and Rudberg, 2005) (see Figure 1). In the ETO class the product is linked to a specific customer order during the early phase of the value creation process. MTO covers products from a predefined range which will be produced after an order intake. The ATO class contains products whose components are manufactured based on forecasts and assembled after the receipt of an order. Products of MTS are characterized by a late CODP and a very low degree of customization (Porter et al., 1999). Following the previous explanations, products of the mechanical engineering industry can be classified as ETO products – even though in practice products often can be characterized by more than one oh those classes.
In the mechanical engineering industry an order fulfillment process basically covers three phases: *Project Acquisition*, *Realization of the Project*, *Service and Customer Support*. Mapping the early CODP of ETO products on the three phases of an order fulfillment process in the mechanical engineering industry, the *Project Acquisition phase* must be a significant driver for variants. This is expressed by Figure 1. For meeting customers' requirements, project specific variants are created without taking their reusability in other projects into account. Although standard products or variants of further projects meet the customer's requirements in an appropriate way, unneeded variants are created. Reasons for this are a high pressure to sell products, unsuitable support systems during the *Project Acquisition phase* and insufficient technical knowledge about the product (Foerster 2003). Thus, the sales department offers highly customized products without being able to estimate the change impacts. Time and cost consuming variants are the results. Our field of action is closing the existing gap between *Project Acquisition* and *Realization of the project*, especially between sales department and engineering. Our overall aim is the improvement of order fulfillment processes within the mechanical engineering industry.

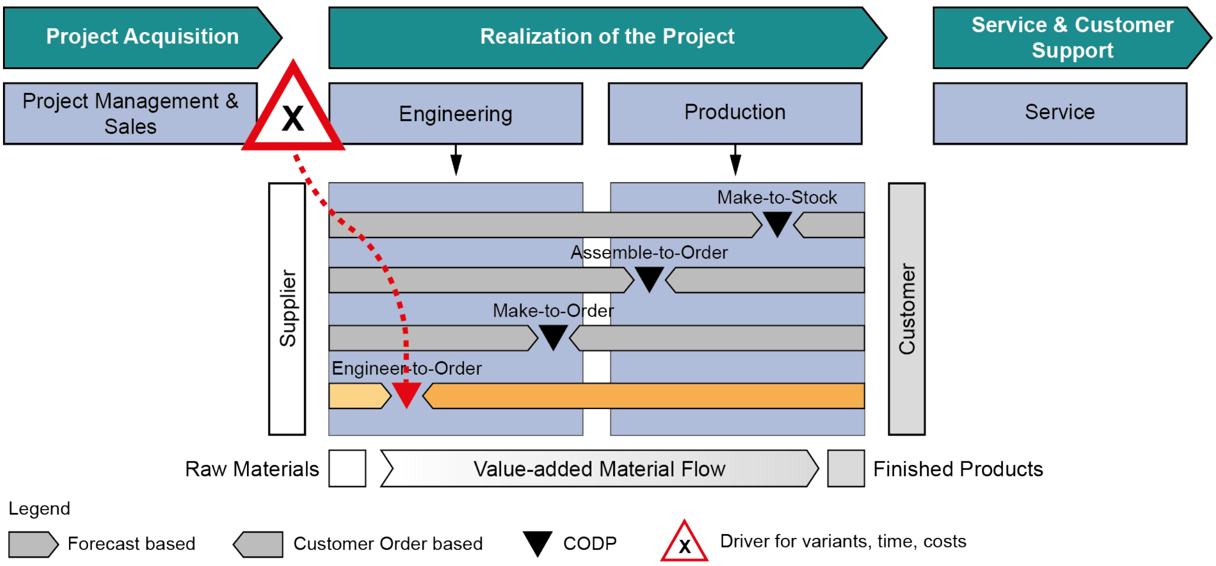

Figure 1: Typical CODPs mapped to an order fulfillment process in the mechanical engineering industry (according to Wikner and Rudner, 2005)

Regarding the *Project Acquisition phase* and the transition to the *Realization of the Project* following challenges are important to focus on: **interdisciplinary understanding of the system for all stakeholders**; **modular system architecture design (high degree of standardization for easy adaption and combination)**; **communication inside the company and with customers**. The interdisciplinary approach of Systems Engineering and Model-Based Systems Engineering meet the mentioned challenges. Therefore we analyse the usability and benefits of MBSE especially for the addressed gap between *Project Acquisition phase* and the *Realization of the Project*.

3 SYSTEMS ENGINEERING AND MODEL-BASED SYSTEMS ENGINEERING

Systems Engineering is a holistic approach to enable the realization of successful systems in an efficient way. SE includes systems thinking, discipline specific engineering approaches (methods, tools and procedure models), management aspects and human sciences (INCOSE, 2010; BKCASE, 2012; 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 solve a complex development task efficiently. The collaborative consideration of system and project are the core aspects of SE (see Figure 2) (Gausemeier et al. 2013).

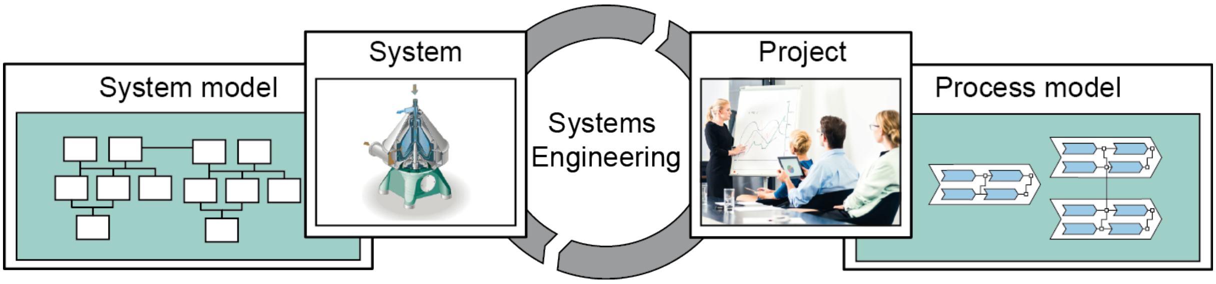

Figure 2: Collaborative Consideration of System and Project – Core Aspects of SE (according to Gausemeier et al. 2013)

Model-Based Systems Engineering 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. (Gausemeier et al., 2013, INCOSE, 2007).
MBSE focusses on a system model which allows a holistic, domain-spanning perspective on the system. The system model constitutes the basis for communication and cooperation in a multidisciplinary project environment. It helps to reason about a problem and pursues the goal of controlling product complexity by being transparent (INCOSE, 2007; Kaiser et al., 2013). At first, the description of the system aspects by suitable diagrams gains transparency. A method (e.g. SysMod (Weilkiens, 2014)), 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 kind of diagrams they are described. Secondly, transparency is reached by associating related information objects via traceability links. 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. Figure 3 (left side) illustrates an excerpt of the active structure of a separator bowl based on CONSENS. The separator serves as an example to explain our approach in section 4.

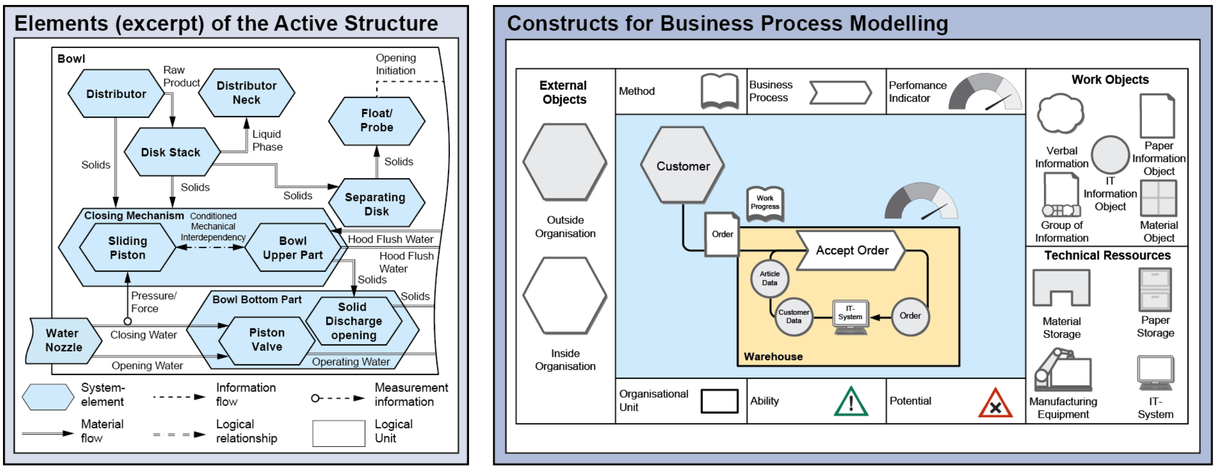

Figure 3: Elements (excerpt) of the Active Structure and Constructs for Business Process Modelling (according to Gausemeier and Plass, 2014)

Next to the system, the consideration of the project is essential for Systems Engineering. The project design encompasses the coordination of activities while taking given resources, time, cost and quality aspects into account. According to the number of protagonists in a project, the complexity of project design increases (Gausemeier et al., 2013). Therefore a transparent and comprehensible description of business processes is necessary. In literature many methods for modelling business processes exist, e.g. SADT (Ross, 1985), ARIS (Scheer, 2001), BPMN (OMG, 2011) or OMEGA (Gausemeier and Plass, 2014). Because of the easy and concise visualization we use OMEGA for the description of order fulfillment processes. OMEGA allows an entire modelling of an organization as a fundament for analysing and planning value creation processes. Figure 3 illustrates the constructs of OMEGA.
As illustrated in figure 4 the approaches of Systems Engineering and Model-Based Systems Engineering are suitable to improve the order fulfillment processes. Focussing on *Project Acquisition* and *Realization of the Project,* MBSE, especially the active structure, is useful to create a common understanding of the system. On the one hand this is important to ensure a sufficient technical knowledge of the system and on the other hand the communication between departments within one company or between customer and company can be improved. Furthermore, MBSE is useful to analyse the existing system in an interdisciplinary way and to create adaptable, optimized system architectures. Consequently we use MBSE in our approach to improve order fulfillment processes.

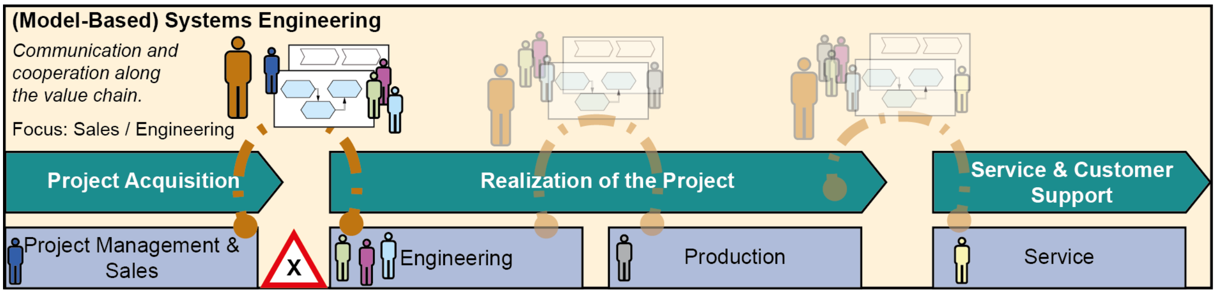

Figure 4: Starting point to improve order fulfillment processes with MBSE

4 APPROACH TO IMPROVE ORDER FULFILLMENT PROCECESS WITH MBSE

To explain our results in this section, we will use the example of a separator (see figure 5). A centrifugal separator separates substances and solids from liquids or separates liquid mixtures at the same time as removing solids. The function bases 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. Markets for separators are beverages, breweries, chemistry, dairy, energy, environment, marine, oil, gas and many more. The high number of possible applications causes a high number of separator types and variants. Various customer needs and highly customized products lead to high efforts in the order fulfillment process.

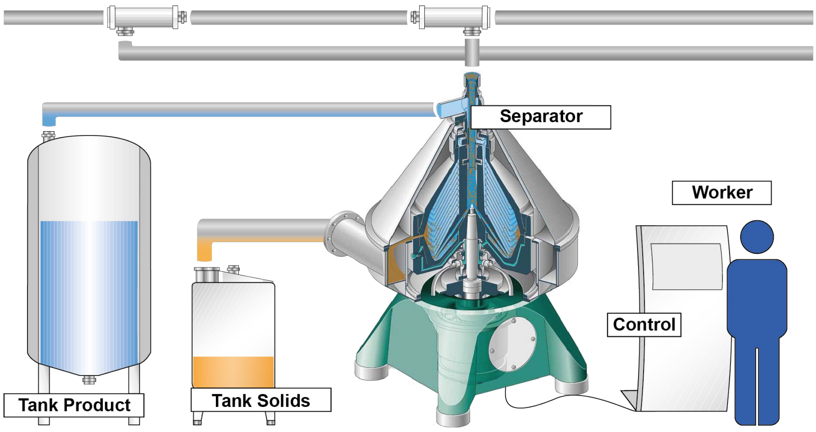

Figure 5: Schematic Illustration of a Separator

Our approach to improve order fulfillment processes with MBSE contains four phases (see figure 6): System and Process Modelling (Phase 1), System and Process Analysis (Phase 2), System and Process Improvement (Phase 3) and Introduction of MBSE to Order Fulfillment Processes (Phase 4). Actvities and results of each phase will be explained below.

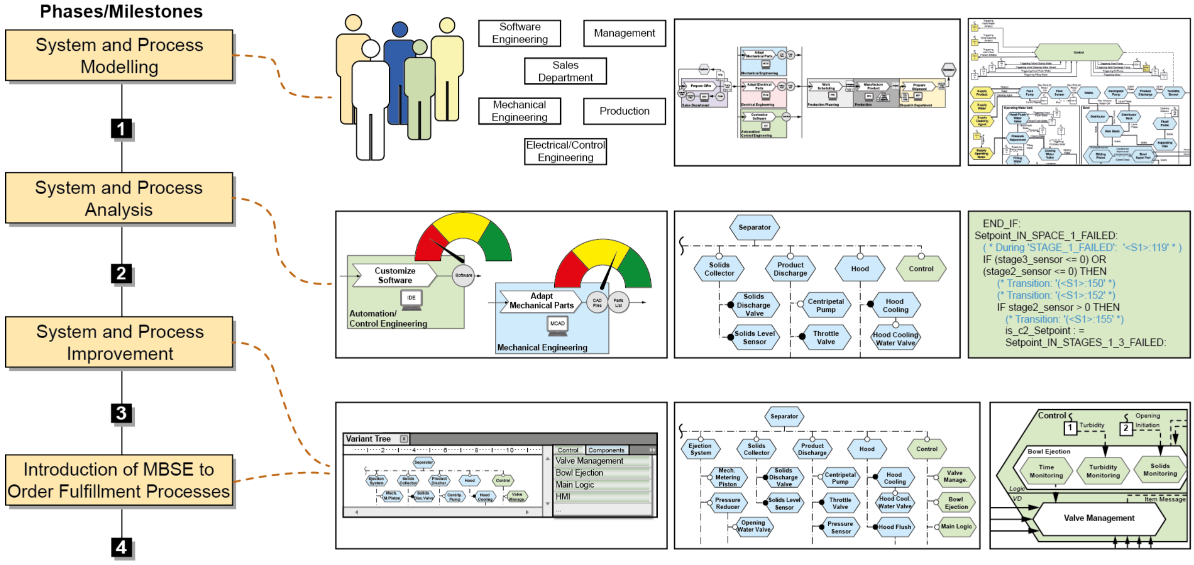

Figure 6: Overview of the approach to improve order fulfillment processes with MBSE

Phase 1 – System and Process Modelling: In the first phase of the approach the system as well as the order fulfillment processes are modelled. For both, system modelling and process modelling, it is important to involve experts of various departments (e.g. mechanical engineering, software engineering, sales department etc.). With interdisciplinary workshops a domain-spanning description of the system and a description of the business processes are created. Regarding the system, it is important to describe the system in a domain-spanning way. That means to describe mechanical parts of the system as well as software parts in equal measure. Therefore the method and modelling language CONSENS is used. CONSENS allows a domain-uncommitted description which cannot be created only with CAD drawings or wiring diagrams. The domain-spanning description expresses all system elements, environment elements and their interrelations. This creates a common understanding of the system. OMEGA is used for the description of the business process. For analysing the order fulfillment processes it is important to describe all process steps during the *Project Acquisition*, the *Realization of the project* and the *Service and Customer Support*. The system and process models form the basis for all following activities.
Figure 7 illustrates the activities of the first phase by means of the separator. The description of the system and the business process were created by involving various disciplines like sales department, mechanical engineering or production. Through interdisciplinary workshops a common understanding of the system and of the business process can be created. A common understanding is important to understand each other's perception. The domain-spanning description of the separator includes elements of hardware and software, environment elements as well as their interrelations. In this phase the separator control is described as a single system element. Following analyses will show that a more detailed description of the control is necessary. The description of the business process shows that mechanical and electrical parts as well as software have to be adapted to meet the customer's requirements. Both the domain-spanning description of the system as well as the description of the business process are important for following phases.

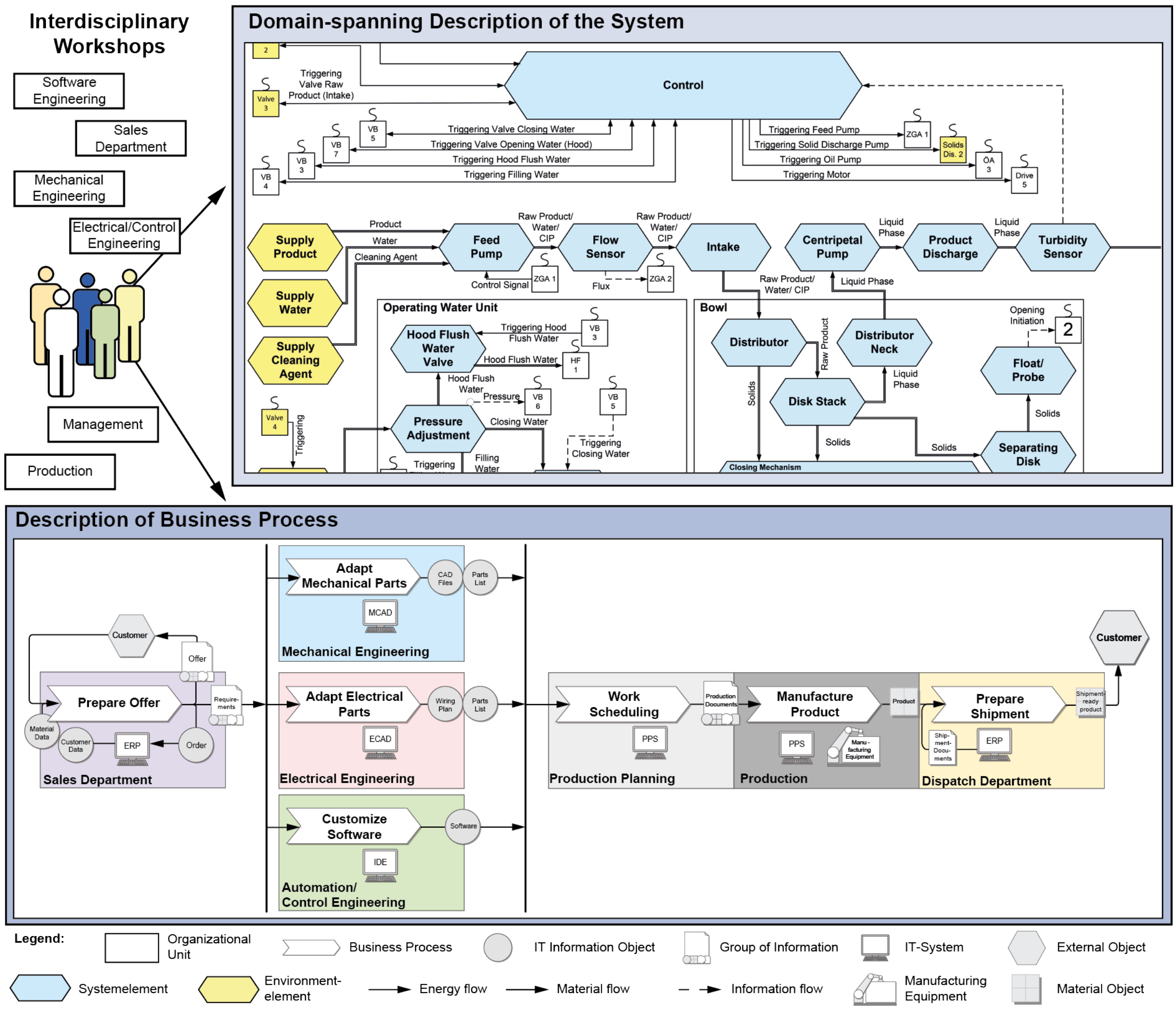

Figure 7: Activities of Phase 1 – System and Process Modelling

Phase 2 – System and Process Analysis: Analysing the system and the business process is the task of the second phase. Regarding the process it is important to identify process steps which generate new variants. Moreover it is important to know which process steps are impacted negatively by a high number of variants. For analysing the system, it is important to analyse the existing variants and the structure of the software. For later improvement activities it is important to know which variants of the system exist. Furthermore it is important to know which elements are necessary 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 with modules, the software is often not structured appropriate.

In the current example, new variants are often created during the preparation of an offer. The sales department uses questionnaires to inquire the customer's requirements. The questionnaire helps to structure the requirements elicitation but it does not support the sales department in consideration of existing variants or change efforts. In consequence of that, non-standardized components arise and adaptions of mechanical, electrical and software parts are needed. The analysis of the business process is shown in the left side of figure 8. Regarding the system analysis (see right side of figure 8), the variants as well as the software structure were analysed. Using a variant tree it is possible to show variants of mechanical parts (e.g. hood) and electrical parts (e.g. pressure sensor) which are both shape-intensive elements. For a complete description of variants, the single components of the control (software-intensive) have to be considered. Therefore an analysis of the control structure is necessary. Regarding the example of use, the software has not a sorted architecture. Consequently, new variants generate high efforts because the software code has to be changed manually. This has a negative impact on the process step *Customize Software*.

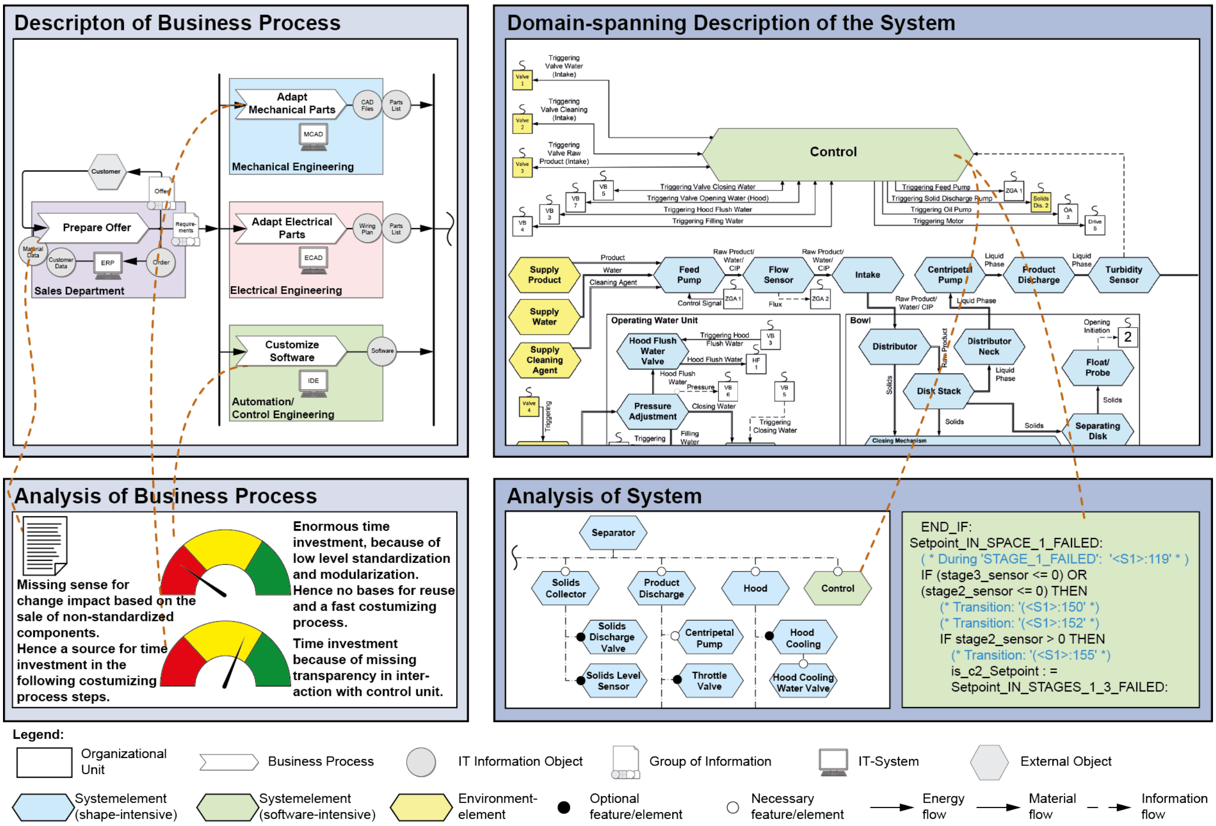

Figure 8: Activities of Phase 2 – System and Process Analysis

Phase 3 – System and Process Improvement: In the third phase of the approach activities for system and process improvement are prepared. Regarding the process, the preparation of an offer is the room for improvement. Instead of using questionnaires, the sales department can use the domain-spanning description of the system to communicate with the customer. The domain-spanning description is helpful for the sales department to gain a better understanding of the system. This is important to estimate efforts for changes which the customer asks for. Additionally, a configurator supports the sales department to search for a suitable variant for the customer. Regarding the system, an unstructured software architecture causes high change efforts. Thus, it is necessary to structure the software in consideration of functions. Closed function blocks allow a customer specific configuration of the software without high manual efforts. With a functional orientated software architecture and a loose coupling of shape-intensive elements it is possible to create mechatronic modules. All elements which are necessary to fulfill a function are consolidated in one mechatronic module. The spatial relations between elements are irrelevant. Mechatronic modules facilitate interdisciplinary communication of changes and reduce change efforts.

Regarding the separator example, customers have diverse needs and requirements. Without suitable tools it is hard to find the ideal product configuration. A product configurator would support the sales department to find a suitable configuration. By using a configurator it is not possible to choose variants which cannot be realized economically. This confines the creation of variants. Figure 9 shows an excerpt of the configurator tool. An important precondition for a configurator is a structured software architecture. Therefore closed function blocks were built (see figure 9). The closed function blocks can be integrated in the variant-tree. After the sales department configured a customer specific separator, the engineering departments can prepare mechanical and electrical parts as well as the software without high change efforts. The closed function blocks allow the creation of mechatronic modules which can be composed customer specifically.

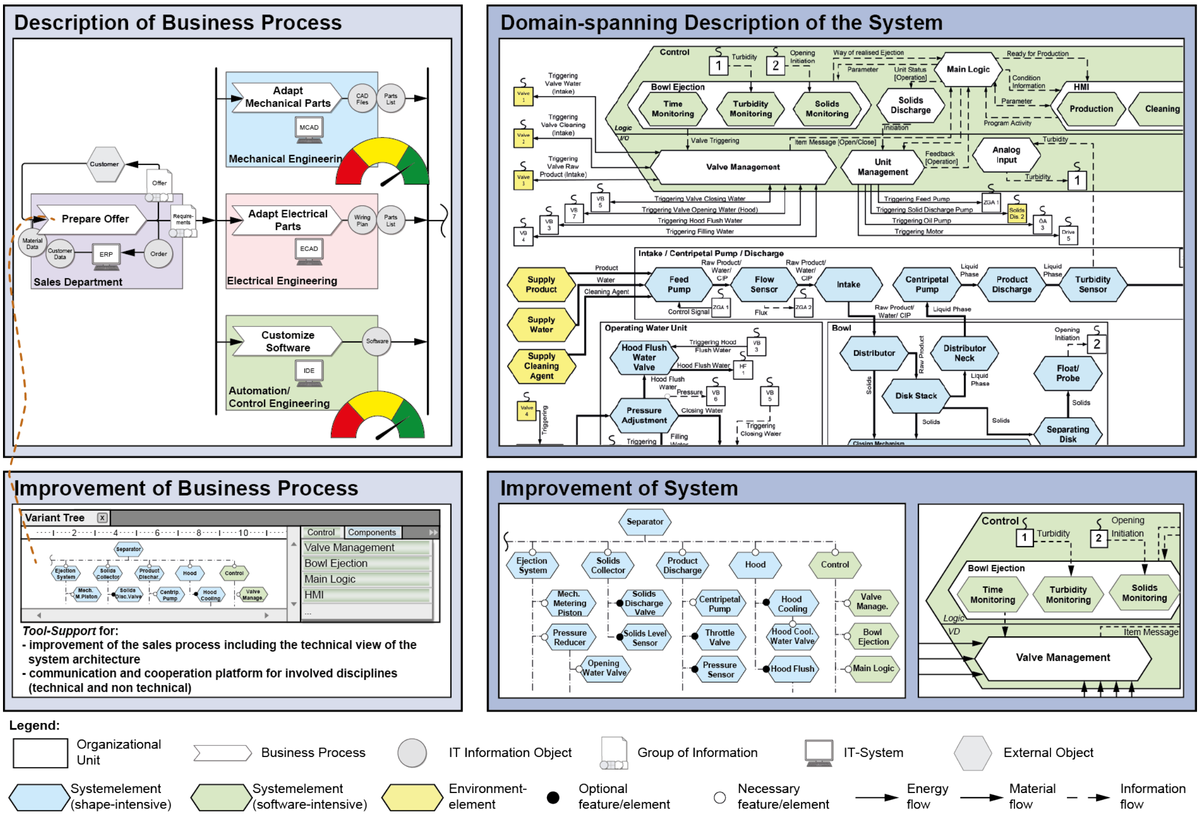

Figure 9: Activities of Phase 3 – System and Process Improvement

Phase 4 - Introduction of MBSE to order fulfillment processes: A sustainable improvement of the order fulfillment process needs MBSE training courses for the sales department and sensitization for change impacts of variants in later phases of the order fulfillment process. Training courses have to address the usage of the domain-spanning description of the system and the configurator. Furthermore, technical knowledge about the system must be teached. In regular meetings between sales department and engineering department, changes of the system as well as new variants have to be discussed.

5 CONCLUSION AND OUTLOOK

Highly customized products dominate in the mechanical engineering industry. Typical products like machine tools, food processing or packaging machines have a high product complexity and low quantities. This generates a high number of variants and leads to high change efforts during the order fulfillment process. Using the customer order decoupling point, the *Project Acquisition phase* was identified as a driver for variants. Main challenges of the order fulfillment process are: interdisciplinary understanding of the system; modular system architecture design; communication inside the company and with customers. Therefore we introduced an approach to improve order fulfillment processes with Model-Based Systems Engineering. In addition we validated our results exemplified by a separator. Our results meet the mentioned challenges as follows: creating a domain-spanning description of the system and the business process to gain a common understanding (Phase 1-2); optimizing the system architecture by defining mechatronic modules (Phase 3); improving the sustainable communication within the company and with customers by training courses and tool support (Phase 3-4). Summing up, our results clarify the supposed benefits of MBSE to improve order fulfillment processes in the mechanical engineering industry.

In our 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). Our aim is to define a reference architecture for Cyber-Physical Systems considering the characteristics of the mechanical engineering industry.

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