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Systematics for an Integrative Modelling of Product and Production System

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Abstract

Due to shorter product life-cycles, manufacturing companies nowadays must maximize efficiency in development and planning of products and production systems. To achieve this, new methods and tools are required to cope with increasing product variants and system complexity. Therefore, we propose a holistic systematics to develop a consistent, model-based architecture for products, production systems and their interdependencies. For this, we give a domain-specific ontology containing model elements, relationships and attributes. Ontology and systematics are applied to a use-case from the automotive industry. In summary, the approach deals with modern-day demands in engineering by considering interdependencies between product and production systems.

Keywords: *Model-based systems engineering; Advanced systems engineering; Product-Production-CoDesign.*

1. Introduction

Due to shorter product life cycles, the frequency of developing and planning products and production systems increases. In addition, because of the demand for a shorter time-to-market and individual products, manufacturers nowadays need to reduce time and maximize efficiency in development and planning of products and production systems. [1] To cope with increasing product variants and system complexity, new methods and tools supporting humans in production planning are required [2].

Especially within the automotive industry, high cost pressures are forcing manufacturers to constantly improve repetitive product variant-specific engineering processes. Here, a holistic view of designing products and planning corresponding production systems holds immense potential [3]. The analysis of product properties and their impact on production as well as interdependencies between the two in general require a standardized representation and manageable methods.

Problem Description:

Through scientific discussions within the joint research project *MoSyS* (see Sec. Acknowledgements), the information gap caused by different information systems and domain models between the various departments of product development, process development and production is identified as key challenge facing companies such as *BENTELER Automobiltechnik GmbH* (in short: *BENTELER*). Here, method and tool support in the development of holistic models remain rare [4]. Such models need to be consistent and holistic in order to formalize interdependencies between product, process and production resources [5]. In addition, a systematic procedure describing the modeling process as well as continuous and easy extensibility are of central importance. Lastly, especially repetitive engineering activities call for the identification of

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reusable modules in order to exploit efficiency potentials by ultimately reducing iterations [3].

Therefore, this article proposes a holistic systematics to develop a consistent, model-based architecture for products, production systems and their interdependencies aiming at fulfilling all demands stated above. For this, we give a domain-specific ontology containing model elements, relationships and attributes as well as a step-by-step design approach.

Structure:

This article is structured as follows: Section 2 summarizes a comprehensive review of relevant literature resulting in three research questions, which are given in Section 3. The ontology as well as the methodical approach for the development of a consistent, model-based architecture for products, production systems and their interdependencies are outlined in Section 4 and 5. Early findings from applying ontology and method are described in Section 6. Section 7 concludes and gives an overview about research activities extending the approach.

2. Fields of Action

2.1. Approaches for the Integrative Development of Products and Production Systems

In many cases, multidisciplinary engineering cannot be a stringent sequence of process steps as mentioned in the ISO 15288. Engineering is becoming more agile, and activities are increasingly iterative. In addition, the well-established V-Model does not adequately address all preceding of subsequent phases. Here, Albers and Lanza envision *Product-Production-CoDesign* (PPCD) as an approach of integrated product and production engineering across generations and life cycles of products and production systems [4].

Another approach considering the iterative development as well as three relevant phases of the product life cycle is the 3-cycle-model of product engineering by Gausemeier and Plass [6]. The first cycle describes three activities within the strategic product planning, the second deals with three activities for product development and the third considers the production system development.

The *integrated Product engineering Model* (iPeM) is an integrated approach that specifically addresses the interface between process management and engineering, thus enabling a consideration of the interactions between engineering activities, requirements, results and methods [7]. The iPeM forms a generic meta-model that describes the product development process on the basis of the system triple as well as the continuous interaction of the system of objectives, the system of objects and the operation system [8]. The goal of this interaction is to transform the system of objectives into the system of objects. The activities of the iPeM can be divided into macro- and micro-activities and arranged chronologically in the phase model [9]. While macro-activities address relevant fields of action of product development, micro-activities form iteratively recurring activities of technical problem solving [7].

One applied method for integrating product development and production planning is the approach of Jacob et al. Herein, the parametrized requirements of a product are compared with the abilities of potential manufacturing technologies. An optimal match is determined by iteratively adapting products and manufacturing technologies and utilizing the degrees of freedom on both sides. [10] However, with increasingly complex systems, these characteristics of product and production need to be explicitly formalized by modeling interdependencies between product and production system.

Here, *Model-Based Systems Engineering* (MBSE) is an approach established in the field of developing mechatronic systems that could also lead to advantages in the integrative development of products and production systems.

2.2. Model-Based Systems Engineering

According to the definition of the *International Council on Systems Engineering* (INCOSE) MBSE is “the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases” [11]. Therein, MBSE denotes the use of a central, interconnected system model instead of a multitude of (unlinked) documents or other artifacts. In this way, MBSE holds the promise of improving information management in product engineering, e.g. by improving communications among developers or improving product quality through unambiguous models of the system in development [11]

Delligatti notes, that in order to apply MBSE three pillars have to be considered integratively: a modeling language, a modeling method and a modeling tool [12]. Further work, e.g. Holt and Perry, add the use of an architecture framework consisting of a set of viewpoints as filters on the model [13]. Therein, the notion of viewpoints is closely related to the descriptions of the ISO 42010 for describing an architecture in systems and software engineering [14]. A viewpoint is oriented on one or more concerns of stakeholders of created models and establishes the foundation for a view. In this way, a viewpoint may be understood as a template for a specific view that represents a part of a model, e.g. in form of a diagram [13].

The following paragraphs will detail a selection of language, methods and tools for MBSE.

Languages:

The de-facto standard modeling language for MBSE is the *Systems Modeling Language* (SysML) [15]. SysML can be used to model system requirements, behavior, structure and constraints/parametric relations as well as interdependencies among them [16]. SysML is a formalized graphical modeling language that defines elements that can be used for modeling as well as for a set of diagrams [16]. SysML can be extended using so-called *profiles* to further detail the modeling language and customize it on the desired application [16]. Following this understanding, Holt and Perry present an approach of defining an (implementation neutral) ontology containing terms and classes to be used for modeling [13]. By the use of a profile, this ontology can be used to extend the SysML and thus be available to use in SysML-modeling tools.

Methods:

The CONSENS specification technique corresponds to a methodical procedure for the development of product and production system [17]. Essential aspects for the system specifications of complex mechatronic systems and their interactions as well as the interdependencies to the production system are described in partial models. Although it is possible to describe interactions, there is a lack of a concrete syntax.

As a result of the research project mecPro², an approach for model-based development of products and production systems is proposed [18]. The approach consists of the integration of a process framework to describe process modules and activities in product engineering, as well as an architecture framework. The latter complies with the descriptions of Holt and Perry mentioned above. An ontology describing elements and relations used for modeling is developed and implemented in a SysML-profile. Therein, product features are modeled as a connection to the production processes of the production system. Production processes are concretized using modeled production procedures. Between the production procedures and the production resources (e.g. machines), relations can be modeled. In addition, the modeling of production process capabilities of a resource is foreseen [19]. Based on the ontology, viewpoints and views are defined addressing specific subsets of the ontology based on a concern. Following the approach, the viewpoints are used by allocating stakeholder-roles to perform activities of the process framework [18].

Similarly, within a predecessor research project *I4TP*, Mandel et al. propose an ontology for integrative modeling of product and production systems [5]. In addition, a method is presented to model and analyze the traceability between modeled functions, sub-system and components with manufacturing relevant features, production processes and production modules (comparable to "resources" from the mecPro² ontology). The display and analysis of this traceability is then used to support methods for impact and risk analysis.

Tools:

The integration of different domains and managing the complexity of multidisciplinary engineering processes also call for tool support. However, due to the short software release cycles and the customizability of many tools an overview of different MBSE software tools is not given within this article. For the application of the presented approach the authors used Cameo Systems Modeler by Dassault Systems.

2.3. Bottom Line

To sum up, there are several approaches considering an integration of product and production system engineering. However, high-level methods such as the 3-cycle-model and iPeM are abstract and do not address the explicit modeling of systems using e.g. an ontology. Modeling approaches such as CONSENS, mecPro² or the results from *I4TP* [20] already cover ontologies and methods for an integrated modeling of product and production systems. However, none of those approaches appears to be comprehensively used in industrial practice.

In a nutshell, for developing a consistent, model-based architecture description, there remains a demand for a holistic ontology covering relevant model elements, relationships and attributes from the domains of product and production system development. In doing so, several research questions arise, which are presented in the following.

3. Research Questions

As evaluated above there are several motivators for integrated product and production engineering. The aim of this research is to define a holistic systematic to develop a consistent, model-based architecture for products, production systems and their interdependencies. This leads to the following research questions (RQ):

1. What is needed to describe and model relevant aspects in an integrative product and production development? (Section 4)
2. How can integrative product and production models be developed? (Section 5)
3. How can the findings be applied to a company specific use case? (Section 6)

To answer these questions, this article gives a domain-specific ontology containing model elements, relationships and attributes (RQ1) and a step-by-step method to consistently model product and production systems in different scenarios (RQ2). Lastly, a real-world example serving as an application use case shows how to cope with some of today's demands and validates the benefits of the presented systematics (RQ3).

4. Ontology

In order to answer RQ1, an ontology containing what is needed to describe and model relevant aspects for the description of Product-Production-Systems is developed. Therefore, relevant aspects must be identified that are sufficiently addressed by the elements and relationships contained in the ontology. In the context of the joint project *MoSyS*, the following aspects and requirements for a system architecture and for the description of integrative product-production systems were identified together with experts from product development and production planning at *BENTELER*: Firstly, the production architecture should be structured by the same aspects (Problem Space, Requirements, Functional, Logical and Physical) as the product architecture, see Fig. 1. This is to allow a consistent integration of the production system into the product-production architecture.

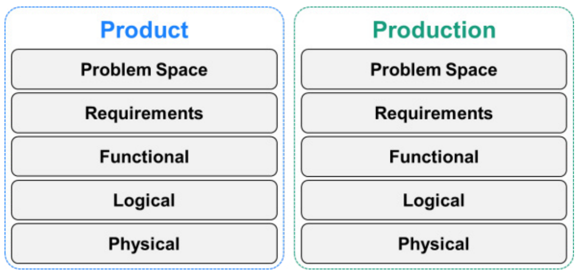

Fig. 1. Equal Structuring of the Product-Production-Ontology.

In addition, it should be possible to model production-specific processes in a time sequence and to connect them to the resources required to execute the processes. At the logical level, the resources should be modeled as non-specific logical resources, e.g., as a welding cell. The physical level should contain a physical resource, e.g., by referring to a specific machine via a connection. Physical operating resources thus have clear capacities and capabilities that are intended to satisfy product-side requirements.

Requirements: Within processes, different features such as weld seams or drill holes are realized. These should be connected with the associated process. Similar to the equipment, there should be logical and physical features. While a logical feature represents a drill hole or a weld seam, physical features refer to a production drawing e.g. containing further details, such as tolerances. Features exist only in connection with one or more structural elements of the product, such as a component or subsystem. In addition to the relation between feature and structural element, structural elements should also be able to be modeled as logical and physical elements, enabling modeling with different levels of specification. Logical structural elements of the product architecture are also connected to functional elements and thus implicitly to functional requirements as well as directly to non-functional requirements and should be taken into account in the holistic development of the product-production-system. In addition, it should be possible to connect product-side elements with production-side processes in order to be able to represent which elements and assemblies with which already realized features enter a process as input and get transformed to an output. For example, it should be possible to check directly whether the accessibility of the production process or the maximum capacity of a physical resource is affected by the assembly entering the process. In addition, inconsistencies in the model should be avoided. Thus, changes in the model should only occur at one point and be propagated throughout.

In the following, an ontology (Fig. 2) is presented that addresses the mentioned requirements by introducing specific elements and relationships. In order to represent production specific processes and the features realized in processes, the element types «process» and «logical feature» are introduced and connected to each other. Furthermore, both «logical element» and «production related assembly» form input or output of processes and thus enable the representation of the chronological sequence of processes. With the element type «production related assembly» logical elements and features are summarized, which come as output from a process and go as an input into the next process. Logical features and logical elements are specified by the elements «physical feature» and «physical element». On the production side, the element «process» is allocated to an element «logical resource» which is necessary for the execution of the process and which is specified by the element type «physical resource». The aspect of consistency is addressed by using only relevant relations. For example, to identify which physical elements are used on a specific physical resource, one must lead to the specified logical resource, then to the allocated process, then to the assembly attached to the output, then to the logical elements, and finally to the physical elements. If a relationship is changed within this chain, the physical elements associated with the physical resource also change.

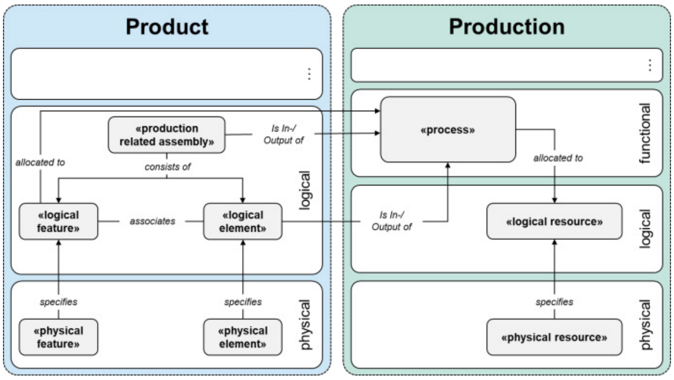

Fig. 2. Product-Production-Ontology.

The presented ontology supports a consistent modeling of the product-production-system. Modeling on different levels of concretization is enabled by using logical and physical elements and features. Production related assemblies are considered, which form the input to a process and thus supports an evaluation of e.g. the accessibility or the required storage capacity of resources.

5. Modeling Method

With the aim to answer RQ2, in the following a method for the continuous development and modelling of product and production system is described. It describes an abstract procedure that provides a rough guideline but is understood as an iterative and flexibly adaptable procedure. Fig. 3 illustrates the approach, which outlines the basic activities to create an integrative model and which is described in the following.

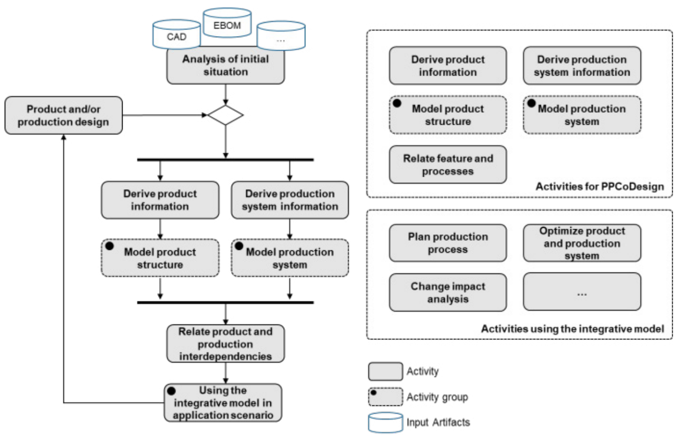

Fig. 3. Method for Developing Product-Production-Models.

The basis for the method are first concepts, both for the product and the production system. In the first step, the database is analyzed and, if necessary, supplemented by further input documents, such as CAD-files. Based on this, the relevant information is extracted, and the data types (classes see Sec. 4) of the information are determined. The classes are used to build the model and fill it with concrete content. This is done in parallel for the product and production system.

As described in Sec. 2, there are different interdependencies between product and production systems. Using the benefits of the model-based approach as well as the described ontology in Sec. 4, we propose to relate aspects of the product, mainly the logical features, and the production system processes in order to create a consistent and integrative model. The resulting model is now a basis for numerous applications that have partially been tested as part of the research project *MoSyS*. One example was the use of the integrated model for the design of optimal production processes based on the product specification. Schäfer et al. propose to use the model for deriving optimal production sequences from customer product data which is validated using welding processes. This supports users in automatically planning new production systems based on already designed new product variants using knowledge and interdependencies from past product variants. [21] Another application, which addresses the development process in industrial companies in particular, is the use of the traceability of the model for change processes both of product features and in the production systems.

As illustrated in Fig. 4, the presented approach gives an outline of activities necessary to develop an integrated model. Based on the input documents and the state of the development of the product and/or production system, activities as part of the modelling process can change or be used at a later stage.

6. Application

To tackle RQ3, the design approach is applied to a real-world example from the automotive industry. The aim is to model a specific product, its production system and their interdependencies by applying the design approach from Sec. 5. The resulting model is exemplary implemented within the software tool Cameo Systems Modeler using a SysML-profile based on the ontology from Sec. 4. The application example is provided by *BENTELER*, which is also facing the need for more efficient engineering processes due to shorter product life cycles and increasing system complexity. The example deals with the development and production of a *Rear Twist Beam* (RTB), which is a welded steel assembly containing several elements such as a torsion profile and a wheel plate and it is produced on a modular assembly line containing welding centres, lasers, reworking and further.

In the following the example is transferred step by step into a system model according to the design approach. CAD models of the RTB product, technical drawings of the modular production line, requirements and expert knowledge from different disciplines are used as a starting point. The first step is to identify relevant information types and for these determine data types (classes) based on the ontology in Sec. 4. The CAD model of the RTB (see Fig. 4) contains physical components («physical element»), weld seams («physical feature», holes («physical feature»), tolerances («logical feature») and further. Each of these classes can be described by different parameters such as length, position, tolerance, radius, material, weight and possible interdependencies between these classes.

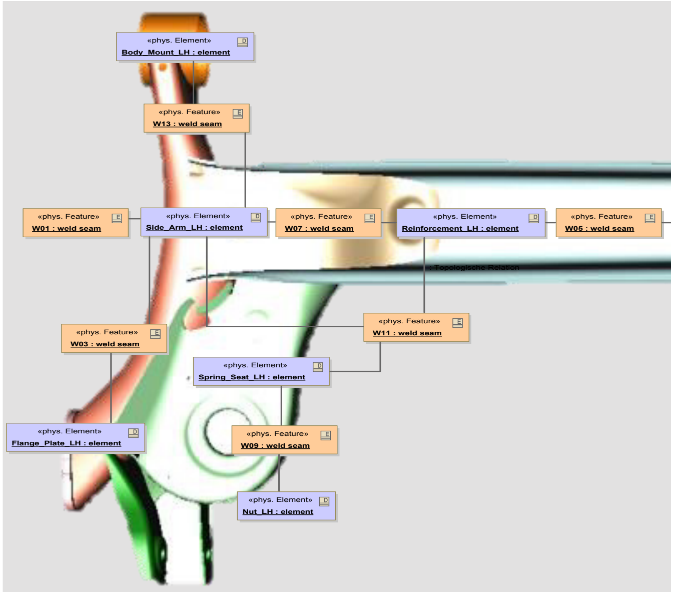

Fig. 4. Excerpt of the modeled Product System.

The modular production system (see Fig. 5) consists of physical resources which are combined to an assembly line. The product gets produced on this line by passing one module after another or skipping parallel modules with the same production step. By analysing the modules of this example, resources such as drilling, welding, laser cutting and reworking (all «logical resource») can be distinguished. To describe the physical resources, parameters such as an ID, process times, possible materials to manufacture and other technical parameters are identified.

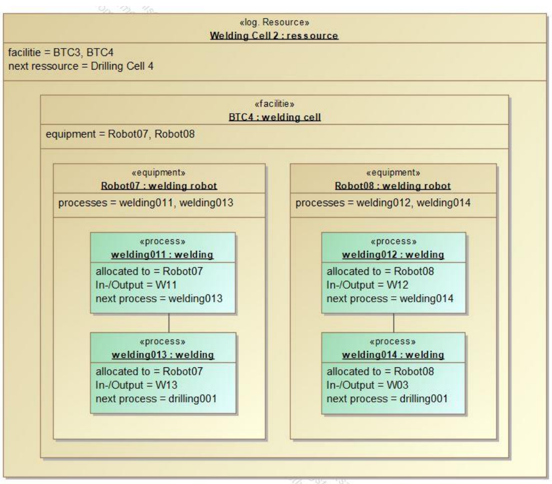

Fig. 5. Excerpt of the modeled Production System.

In the second step processes are defined to connect the product and the production and to define interdependencies. In the example of Fig. 6 a weld seam («logical feature») which is a specified by its length and width from a phys. Feature should be modelled. Therefore, the weld seam is allocated to a process called “Welding 1” («process») which is allocated to a welding cell “Welding Cell 1” («logical resource»). Furthermore, the weld seam connects the two elements “Flange_Plate_LH” and “Side_Arm_LH” («physical element») which are specified by its physical elements. Due to the allocation between product and production, the output of the process “Welding 1” will be a production related assembly, exemplary called “Welding Assembly 1”.

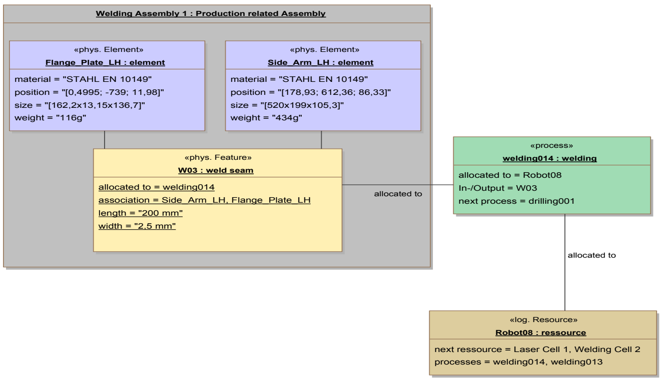

Fig. 6. Exemplary Interdependencies between Product & Production System.

In accordance with this, different processes and elements can be defined and allocations and specifications can be set.

7. Summary and Outlook

This article describes what is needed to model product, production systems and their interdependencies and how such models are developed. For this, the article gives a holistic ontology as well as a method and therefore it tackles increasing demands for applying MBSE at the intersection of product development and production planning. The application of the proposed systematics demonstrates the identification and initial modeling of modules that are reusable in the future ultimately resulting in an efficiency increase within repetitive engineering activities. Here, the consistent use of an ontology also enables Production Planning and Control with regards and interfaces to e.g. OntologySim or else.

Current and future research will focus on using the systematics presented here to analyze effects of changes on the product and production side as well as to identify solution patterns. The former will enable the analysis of the propagation and impact of potential changes. Based on specific changes, a holistic, system-wide propagation analysis can be performed to identify critical areas across products and production. The latter especially tackles the formalization of implicit, historic solution knowledge. Here, a solution pattern describes, for example, the relationship between product properties such as shape, form or material and properties of the production system such as layout, technology or capability. Ultimately, a selection and combination of solution patterns can lead to higher efficiency in repetitive development and planning tasks.

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