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Integration of model based system engineering into the digital twin concept

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Abstract

For some years now, digitalization has made its way into all phases of the product life cycle. With the help of the modeling language SysML, Model-Based Systems Engineering (MBSE) represents a modern approach in product development. At the same time, the technologies of Industrie 4.0 and digital twin are opening up a new level of efficiency to producing companies. But entertainment technology is also finding its way into business: Virtual Reality (VR) provides an immersive and cost-effective way to perceive products in the early stages of product development. In order to provide these with quickly available data for display and simulation, it is worthwhile to expand the MBSE approach. This work describes how a product model can be extended by a simulative function structure. On the one hand, this work describes how the Cameo System Modeler can be used to extend a product model with a simulative functional structure. On the other hand, it explains how to extend an existing product model by modeling the information required to efficiently and consistently translate an Engineering Bill of Materials (EBOM) into a Manufacturing Bill of Materials (MBOM).

Keywords: Digital Twin; Model Based System Engineering; Industrie 4.0

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1. Introduction

1.1. Industrie 4.0

Industrie 4.0 started in 2010 as a future project of the German government's high-tech strategy. Since then, it has become the driving force for the digital transformation of industry. The main objective of Industrie 4.0 is to improve value-added processes along the entire product life cycle. Further goals include increasing product and process flexibility as well as quality and resilience. In Industrie 4.0 Machines and systems that have both a physical and a networked part, i.e. a digital representation, are called cyber-physical systems (CPS) and form one of the foundations of Industrie 4.0. Each physical device has a virtual counterpart in the form of a digital representation of itself. CPS are thus able to communicate with each other and with people, as well as to monitor themselves. By using these technologies, a high degree of flexibility can be achieved, which makes it possible to react dynamically to customer requests and adaptations and thus to guarantee the production of individual, but nevertheless inexpensive products. The Internet of Things enables optimized decision-making on the basis of data that is much easier to collect, expanded possibilities through new service approaches and better behavior of the labor market with regard to demographic change and work-life balance [1] [2].

1.2. RAMI 4.0

The entire picture of a networked company is obtained by considering the Reference Architecture Model Industrie 4.0 (RAMI 4.0) [3]. Considering the product life cycle (trend axis), the model projects different levels of digitization (architecture axis) onto the hierarchical levels of a manufacturing company (hierarchy axis). The model assumes that each level of the hierarchy axis (product, field device, control, production plant,

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production module, connected world, company) can exist in the different states. It basically differentiates between types and instances. In line with the V-Model, a product is available as a type if it is developed and used and updated in the developed status. During production, instances are created from types (ratio 1: n). After production, each product produced is in the use or maintenance phase. As already mentioned, all levels of the hierarchy axis can be in all life cycle phases. [3]

1.3. Digital Twin

The cyber-physical systems of Industrie 4.0 depend as already mentioned, among other things, on a continuous digital information flow along the life cycle phases. A major challenge here is virtual product development, where an exact digital representation of the product, its assemblies and its individual parts is created.

This product representation is then used for analysis, simulation and optimization. After release of the product representation, workflows and NC data for the control of production machines are derived and generated. The physical production of the individual parts, assemblies and the complete product follows. At the same time, the digital representation of the individual parts, assemblies and the complete product is created. This is the birth of the so-called digital twins.

Despite the existence of different definitions of the digital twin, there are some elements that form an intersection. Glaessgen and Stargel list these as follows [4]:

- exact physical image (microscopic and macroscopic) of the physical twin,
- highly accurate physical model (thermal, fluid dynamic, elastostatic, etc.) of the physical twin,
- bidirectional connection to the physical twin for updates of the current state via the sensor system and for control of the physical twin via the digital twin,
- fleet information from other digital twins of related products
- other historical and other available data.

The digital twin thus contains on the one hand an accurate representation of reality, which is used for simulations, optimizations and predictions, and on the other hand data from earlier life phases and from related products. This combination of data storage and simulation environment is available in various forms in most definitions and applications. [2]

The challenge is to use a method for the system modelling of the Digital Twin at through the entire product life cycle. The focus should be on the transformation border between the virtual phase to the physical phase. It should be located in the work preparation phase, wherein the interlink of the virtual product with its production process through the production resource, which will be produce the physical product.

2. State of the art and challenges in Industrie 4.0

2.1. Product Life Cycle (PLC)

The product life cycle includes the planning and development of a product, the planning of the associated equipment, resources and processes, as well as production, use and recycling [5]. Since an ICT infrastructure is to be set up as part of this thesis, the information technology perspective on the PLC is of central importance.

The product creation process itself comprises the phases of product planning, design, work preparation and manufacturing. The first three phases additionally form the product development [6], in which the product is defined, manufacturing and assembly documents are created and the tools necessary for production are developed [7].

2.2. V-Model

The V-model is defined in VDI guideline 2206 and offers a larger and generally recognized view of the product development process. The V-Model is divided in three central phases: The system design takes up the requirements placed on the product and forms a cross-domain solution concept that describes the logical and physical effects of the product. This is followed by the phase of the domain-specific design, which includes the separately worked out specification of the solution concept in the respective disciplines. Once the critical functions have been fulfilled, the domain-specific solutions are brought together in the system integration phase under constant reinsurance against the original solution concept and the requirements. All phases are supported by models and simulations. The output of the V-Model is the finished product. The V-Model can be applied to a variety of different scenarios and domains and forms a central starting point for every development process [8].

RFLP stands for Requirements Engineering, Functional Design, Logical Design and Physical Design. The individual components are also called views [9]. It organizes systematic product development from system analysis to system development along the left half of the V-Model (see Figure 1). Requirements structures show why a product is developed and clarify the customer needs and the goals of the company. Functional objects define the goal and desired behavior of the product, which are implemented in terms of function and mode of action by the logical structures. Physical parts ultimately determine the form and final function of the individual components. It makes the product accessible to the end customer. [9]

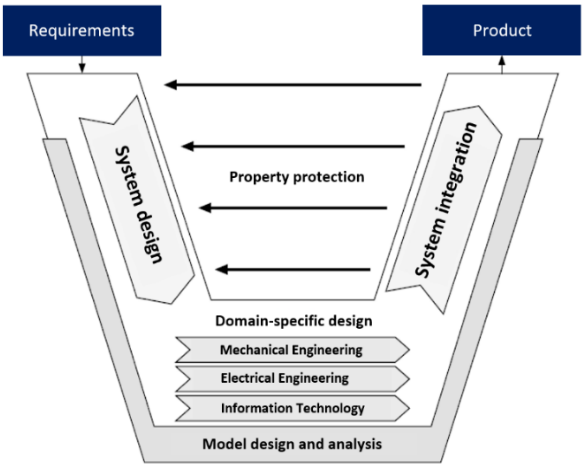

Figure 1: V-Model [8]

The approach of interlink the product with its production process through the production resource (PPR) is an abbreviation for the three terms product, process and resource, on the basis of which an integrated factory data model for product and process planning is built [11] [12]. The central node of the model is the process to which products and resources are assigned. A process (a production process, step, or an operation) describes a manufacturing, assembly or another processing process in which materials or data are processed. The product (a module, an assembly or a single part) is processed, while the resources (a factory, line, station, machine or tool) include all the means required to carry out the process [12] [13] [14].

The aim of the PPR approach is to create a PERT diagram (program evaluation and review technique), which depicts the individual process elements and their temporal consequences in a process-oriented network plan. The processes are linked by material flows and triggered by events, such as the arrival of a material [11] [15] [16].

2.3. Model-based Systems Engineering (MBSE)

Systems engineering is an interdisciplinary science that helps with the analysis, planning and optimal design of complex technical systems [17] and is subordinate to the overall project management of a development project [18].

Model-based systems engineering is a form / further development of systems engineering. It generally includes the use of models to support requirements, design, analysis, verification and validation across all phases of the product lifecycle. In addition, there is communication between system developers (including systems engineering models) and component developers (including physical models) guaranteed. MBSE can be used in particular in early phases of product development to compensate for the uncertainties typical of these phases through iterative development processes (front loading) [19]. The aim is to replace document-centered methods of system technology with a model-based, machine-readable and yet individually viewable system model by questioning the life cycle orientation of the documentation [18] [20] [21].

Weilkiens makes it clear that MBSE succeeds through the inclusion of three important components. MBSE therefore requires a tool in which systems are modeled, a language in which the modeling is carried out and a method, with which the modeling can be successfully implemented. MBSE tools from various commercial software providers are increasingly being used in industry.

The SysML graphical modeling language basically distinguishes nine types of diagrams, divided into three groups: structure diagrams, behavior diagrams and requirement diagrams. All diagram types are provided with abbreviations analogous to the UML identifiers after the corresponding name [18].

A widespread view of the SysML diagrams is the allocation of the diagrams to the Four Pillars of SysML, e.g. by Aleksandraviciene and Morkevicius [22], by Steiner [23] or by Friedenthal et al. [24]. The four pillars divide the diagrams into Structure, Parametrics or Parameters, Requirements and Behavior. Among other things, the special importance of the assurance diagram is emphasized here, since it forms its own pillar without the other diagrams in its class.

2.4. Bills of Material (BOM)

Bills of material are designed for information processing in construction and manufacturing companies elementary. They represent a formally structured directory that contains all components of a product including designation (name and part number), quantity and unit [25].

A fundamental distinction is made between the design parts list and the production parts list:

- Engineering Bill of Materials (EBOM) is generated during the design process and is used to connect with the corresponding drawings (as designed).
- Manufacturing Bill of Materials (MBOM) are production-oriented, flexible Bills of Material (should build) [25] [5].

In principle, the structure of PLM systems corresponds to that of design BOMs, while ERP systems work with production bills of materials to design the production process [26]. Eigner and Stelzer describe concepts of how the distribution of information quantities between PLM and ERP systems can succeed [5]. For all concepts but a conversion of the EBOM (construction bill of materials) into the MBOM (production bill of materials) which in many companies is a time-consuming activity based on the division of labor proves [26].

3. Objectives and Conceptual Structure

In this paper two topics will be presented. First, the extension of a SysML model for modeling and simulation of domain-specific functional structures under the requirements of a digital twin. And second, the extension of a SysML model to support the conversion of an Engineering Bill of Materials (EBOM) into a Manufacturing Bill of Materials (MBOM). The extension of the model in the first topic should show a possibility to quickly calculate relevant system values; extend the structure of the model and not change it fundamentally; provide a central and clear possibility to change simulation values and structures.

The extension of the model in the second topic should show a possibility how the work of the assembly planners can be supported by open-ended specifications of the designers; show

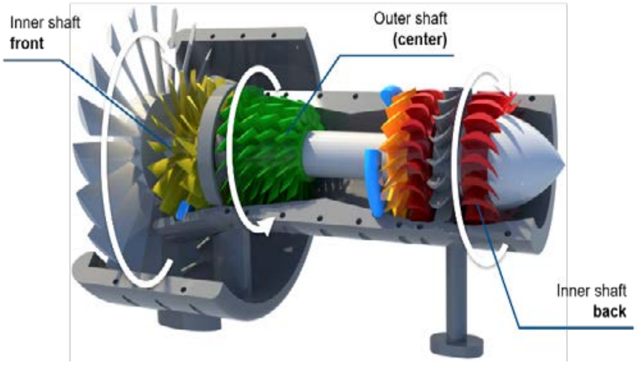

Figure 2: Illustration of a Turbine [29]

how this support can be achieved using an MBSE approach and SysML; extend the structure of the model and not change it fundamentally.

3.1. Extension with the functional component

The extension of a SysML model for modeling and simulation of domain-specific functional structures under the requirements of a digital twin is shown exemplary by using a turbine as an example. This turbine is illustrated in Figure 2.

The first step of the model is to transfer the existing product structure into SysML. This procedure is analogous to the procedure of Zingel, [27] and Wang et al., [28], and does not have to be considered if a SysML model with a corresponding structure already exists.

Next, the effect structure to be investigated is determined. The type of effect structure is not defined, so mechanical, electronic, fluid mechanics, data stream based or many other structures can be investigated. The amount of work is considerably reduced if the structure of the model can be divided into repeating elements and these elements can be broken down to basic action elements. Here the image of the lowest common denominator helps. To identify the effect elements and their underlying structure, competences of the respective discipline are required.

In a next step, the structures of the general effect elements are modeled in SysML in separate internal block diagrams. Mathematical relationships are identified and modeled with the help of constraints. Several constraints are linked by means of binding connectors. Proxy ports transfer incoming or outgoing values across the system boundary of the modeled effect element. Values are either global and valid for all later instances of the general effect element or local and have to be redefined when instantiating. Therefore, the modeling of the functional relationships of a turbine will be finished.

In the next steps, functional elements are added to the product structure, the inheritance of the active structures to the elements is considered and local parameters are redefined. The networking of the functionalized elements from the subsequent step could be done. Once this is complete, the required boundary conditions must be defined and finally the system must be calculated.

3.2. Extension for conversion of EBOMs to MBOMs

The management or conversion of EBOMs to MBOMs is a great challenge due to the additional, usually very specific amount of information. The handling of grouped components (assemblies) makes a big difference between EBOM (construction parts list) and MBOM (production parts list). EBOMs classify components and subassemblies as Engineering Assembly Groups (EAG), while an MBOM contains Manufacturing Assembly Groups (MAG).

Therefore, the extension of a SysML model to support the conversion of an Engineering Bill of Materials (EBOM) into a Manufacturing Bill of Materials (MBOM) shall be presented in the following. The holistic procedure is summarized in Figure 3. After the existing product structure has been transferred to SysML, all occurring interfaces are recorded in a block diagram. Afterwards an assembly matrix is created with the help of applications. The usages are added to the block diagram and the entire presentation is revised. Finally, the MBOM assembly structure is derived.

The approach used here requires neutrality towards plant-specific influences so that an ideal MBOM can be created first, which can then be adapted to a plant. The modeling of interfaces and manufacturing processes as well as their assembly or manufacturing sequence prevents contradictions at a later point in time and describes a method of representing the MBOM without modeling any assembly or manufacturing assemblies. The amount of information modeled is less than that of the finished MBOM. Nevertheless, it contains all required information except for the factory-specific data.

4. Summary and Outlook

Model-Based Systems Engineering takes product development to a new, digital level with the help of the diagram-based modeling language SysML. While SysML, which is kept very open, requires approaches that help to optimally integrate MBSE into a development project, it also allows the language to be used for extended use.

This paper opens up a procedure that makes it possible to extend a component structure in SysML in a way that important parameters for later product design can be derived from it. This approach is especially worthwhile if many recurring parts are used. In addition, libraries for similar components can be created by exporting the structures so that already modeled content can be transferred to other projects. The number of development departments that rely on the use of virtual reality to represent and evaluate products is constantly growing. However, simulations require a lot of time to obtain results, making it difficult to change components in VR and to directly feedback important parameters. The simulative approach described in this paper not only ties in with an existing MBSE model, but is also able to output updated values within seconds.

MBSE, which comes from product development, can also be used in process and resource planning serve. The parts and assemblies defined in the physical phase of the RFLP approach, form the products, that are combined with the linked resources in the PPR approach via the processes. The construction bill of materials (EBOM) structures the products or components on the basis of design-oriented assemblies. These must be able to be translated into assembly-oriented assemblies when converting to a manufacturing bill of materials (MBOM). Additionally, the MBOM production steps and raw materials must be available. Production bills of materials are highly plant-specific, they depend therefore strongly on the available resources. This variability makes the conversion of parts lists very elaborate. Based on the product information, this paper presents a procedure that models and prioritizies information on assembly and manufacturing steps in SysML. The result of this procedure is an MBOM, which can be adapted to the local conditions in the factory in the following.

The contents and findings of this paper already outline a broad spectrum of possible applications and expansions in product and production simulation. The developed procedure for the fast simulation of important system values by the extension with functional components does not only serve a product simulation in virtual reality, but can also be used to carry out a modular series analysis or to determine the orientation of future product ranges. The procedure uses values that have already been determined in the components or clearly demands their redefinition.

The general effect elements, to which the components are generalized, remain untouched, whereby errors are unlikely and changes in the effect structure can be implemented centrally and clearly. In future projects this procedure can be extended and tested on further products. Due to the nature of the engine, this paper refers to a flow simulation, but mechanical or electronic applications are also conceivable. In addition, time-discrete simulations are conceivable in the future; as well as the inclusion of a dynamic view considering the existing masses and mass moments of inertia.

The presented possibility of determining a plant-unspecific manufacturing bill of materials (MBOM) on the basis of an assembly and component structure (EBOM) considers only a small and simplified part of a highly complex discipline. The procedure would have to be tested for a variety of situations and use cases in the manufacturing industry. A concrete project includes the programming of an MBOM generator based on the assembly and component structure, including the assembly or manufacturing matrix that defines the priorities between interfaces to be closed or manufacturing steps. Such an algorithm would be particularly worthwhile for complex products with a large number of individual parts and assemblies. The used principle of priority matrices would have to be checked for a multitude of application scenarios, since the use in software development or in other disciplines is also conceivable. An algorithm that takes the priorities from the SysML model and on this basis creates an optimal MBOM, would also be an optimal interface between a SysML model and an ERP system.

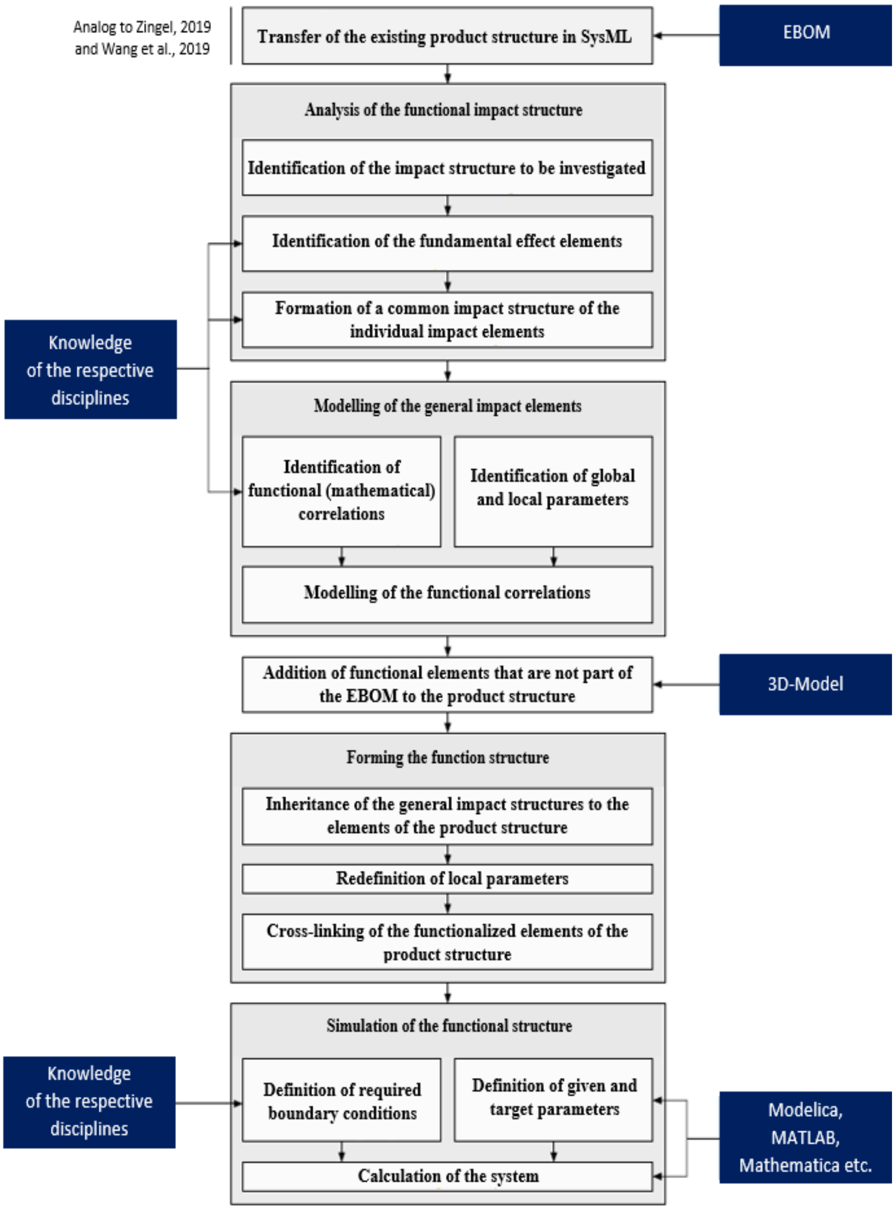
Analog to Zingel, 2019
and Wang et al., 2019

Figure 3: Procedure to extend a SysML model to support the conversion of an EBOM into a MBOM

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