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# FRAMEWORK OF THE EVOLUTION IN VIRTUAL PRODUCT MODELLING AND MODEL MANAGEMENT TOWARDS DIGITIZED ENGINEERING

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## Abstract

Manufacturing industries typically have a strong history and focus on development and production of physical products as their strategic core competence. However, today due to more and more software within mechatronic products one can recognize a rethinking towards interdisciplinary product development. Further, in many areas of manufacturing industries the pure product-oriented focus shifts to the stakeholder (customer) needs. Those two aspects drive the need to describe the physical product not only by geometry and properties, but also by its structure and behavior, as well as to interpret and predict the product and its behavior. This paper is a concept paper to discuss the evolution of virtual product modelling and model management in order to determine potential areas of future research and discussion. Previous and ongoing research work and projects are referenced and brought in context. Moreover, a framework is introduced which helps to position previous, ongoing and future research work as well as industry concepts. Further, it provides boundaries of future steps of evolution in the field of virtual product modelling and model management towards "Digitized Engineering".

**Keywords**: Product Lifecycle Management (PLM), Systems Engineering (SE), Digital / Digitised engineering value chains, Digitised engineering, System Lifecycle Management (SysLM)

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# 1 INTRODUCTION

Manufacturing industries typically have a strong history and focus on development and production of physical products as their strategic core competence. However, today due to more and more software within mechatronic products one can recognize a rethinking towards interdisciplinary product development. Furthermore, in many areas of manufacturing industries the pure product-oriented focus shifts to the stakeholder (customer) needs and experience (Deloitte, 2016). Those two aspects drive the need to describe the physical product not only by geometry and properties, but also by its structure and behavior, and, further, to allow the ability to trace, interpret and predict the product and its behavior in interaction with the environment and customer. Outside the pure product development, global trends of digitalization and digital business models are tremendously changing the manufacturing industries from a business strategy and business model perspective. With these trends - and in combination with the before described product trends - a shift in strategic core competence from a pure product-oriented focus towards services and experiences which are provided and sold to customers is taking place: digital business (Riemensperger, 2016). This tremendously impacts the way of product development - and spreads out to the entire value chain.

This paper is a concept paper to discuss the evolution of virtual product modelling and model management in order to determine potential areas of future research and discussion. First, a brief overview of previous research concerning product modelling and model management approaches, engineering methods and processes as well as IT concepts, tools and technologies is given. Based on this context, a framework is introduced which helps to position previous, ongoing and future research work as well as industry concepts. Further, it provides boundaries and steps of evolution in the field of virtual product modelling and model management towards "Digitized Engineering". Finally, an overview of current research work based on the framework is given. In order to structure this paper and related research work, the following research question was elaborated:

- Which digitalization level of virtual product modelling and model management with respect to applied product modelling approaches, methods, processes, IT tools and technologies is required to enable Digitized Engineering, e.g. Product Lifecycle Management, Model Based Systems Engineering, Digital Twin, Industrial Internet, etc.?

# 2 BRIEF OVERVIEW OF PREVIOUS RESEARCH IN THE AREA OF VIRTUAL PRODUCT MODELLING AND MODEL MANAGEMENT

In this chapter a brief overview of product modelling and model management approaches, engineering methods and processes as well as IT concepts, tools and technologies in the area of virtual product modelling is given. Research work and projects of the Institute for Virtual Product Engineering (VPE) at the University of Kaiserslautern, Germany, are referenced and brought in context.

## 2.1 Enterprise Information Modelling

Supporting federated development processes requires the creation of an efficient software and data structure in the field of engineering. Starting from the product definition, which should be the focus of the data structure, this structure is accessed by individual disciplines such as product development, process planning, manufacturing, logistics, operation, services and accounting in an event-driven process. A separation of different areas or a hierarchical structure is not compatible with increased networking (Scheer, 2015). It is important to consider that a wide range of data must be connected when creating an integrated Enterprise Data Model. Therefore, partially redundant distributed native data, networking data, real-time data, results of big data analysis, and other data are all present and must be taken into account. The SysLM backbone concept described in Chapters 4.1 and 4.2 attempts to meet these requirements with a graph-based, link-oriented data model (Eigner et al., 2013).

## 2.2 Engineering Objects and Engineering Networks

The Engineering Objects approach was introduced and defined over the past ten years based on several research projects and publications (Dankwort et al., 2012; Mogo Nem, 2011). The approach provides a formal frame for the characterisation of products or parts by formally defined Engineering Objects (EOs), supporting Design by Properties with a focus on customer-related and design/engineering-specific product properties as well as product-related process information and supporting the Views and the way of thinking of the people involved in the product development process (PDP). Products or product parts within their related processes are considered as EOs. The focus is on the Description of an EO by its properties and their structure (including product functionalities), according to the "View" of the involved people. The possible Representations of an EO are necessary aids within the PDP. A property of an EO in general is a specific piece of information linked to the EO. A person working in the PDP, who is interacting with an EO with respect to the properties relevant to him, has to consider the property values (numbers, figures, word, etc.). This focus on properties as the Description of a product and on its PDP is a new aspect of product handling within the PDP (Dankwort et al., 2012).

The Engineering Network (EN) concept is a first implementation of the EO approach. The conceptual foundations for the concept have been laid in (Mogo Nem, 2011). The EN consists of a new enhanced and flexible object-oriented meta-model and an appropriate framework for the modelling, structuring and provision of collaborative and integrated multi-disciplinary product data and engineering process models. The EN concept aims at reducing complexity by offering a flexible multidisciplinary information federation backbone and thus reducing the efforts and costs for implementing and customising PLM solutions. Moreover, the EN concept supports the mapping of data into data management systems. Product data models and engineering process models derived from the EN meta-model provide user-specific Views as well as flexible and variable development processes.

## 2.3 Technology Object

Technology Object is part of ongoing research work, aiming to leverage concepts from technology management (TM) to enhance product modelling in the context of PLM. For this reason a framework was introduced to set first boundaries of modelling technologies in the context of product structures and product data (Bitzer and Vielhaber, 2013). For technologies on different levels of granularity this dimension enables the engineer to reflect technology structures. An example of a technology structure could be that the “cyclone technology” and the “ball technology” are located under the technology end item “vacuum cleaner” (Dyson, 2017). By this the engineer is able to reflect interdependencies and create structures between technologies of different levels of granularity.

## 2.4 Modelling and Systems Engineering

Emerging from a document-based approach in the 1960s, today Model-Based Systems Engineering is a concept to model and (re)use engineering information across the lifecycle to meet the stakeholder´s needs (INCOSE, 2016a). To support an either human- and machine-readable approach, the Systems Modeling Language (SysML) was invented by the Object Management Group (OMG) in cooperation with INCOSE. SysML is based on the language and formalism concepts of the OMG UML (Unified Modeling Language) (INCOSE, 2016b; OMG, 2016).

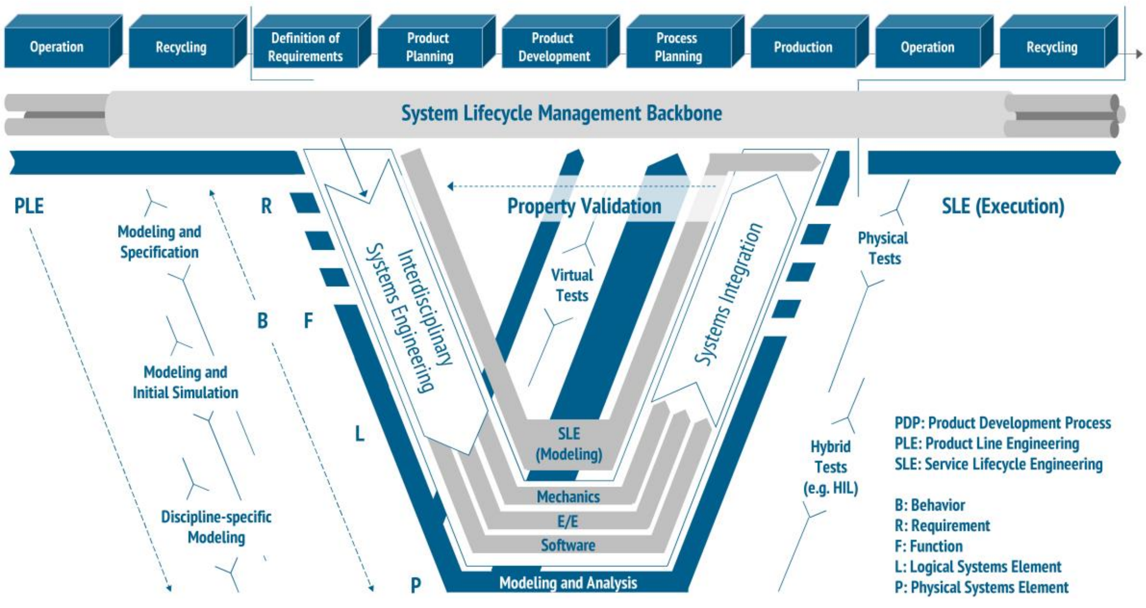


*Figure 1. MVPE-Model - Extended V-Model according to VPE Institute*

SysML models describe systems through requirements, structure and behaviour in a very abstract way, so that these System Models can be used as the 'glue' between the different engineering disciplines. Through such a model, a Product Lifecycle Management (PLM) solution is able to trace information towards a fully digitized engineering approach. Prerequisite is, that System Models are under configuration control (versioning, change and release management etc.) (Muggeo and Pfenning, 2015). Besides new possibilities like interdisciplinary Engineering Change Management (ECM), also the creation and support of digital twins (see Chapter 4.5) is a use for System Models. Figure 1 shows the MVPE-Model, an extension of the VDI guideline 2206 (design methodology for mechatronic systems) (Eigner et al., 2014). The extensions focus on two essential points, the support of the left "wing" of the V-model by methods from model-based systems engineering and on the seamless integration and management of data from the entire product lifecycle by a System Lifecycle Management backbone.

### 2.5 System Lifecycle Management

The products and product systems made possible by the Industrial Internet are customized to suit an individual's needs and no longer require the individual to adjust him- or herself to suit the product. Today, the focus is on the product system. The complexity of the product and production systems continues to rise. Traceability must be ensured at all times in order to manage this complexity. Currently, traceability within conventional PLM solutions is only limited to the link between product requirements and the items in the bill of materials. As a development and extension of PLM, System Lifecycle Management (SysLM) is the next step. SysLM is a general information management solution extending PLM to the early development phase and all disciplines along the lifecycle including services (Eigner, 2016). SysLM is the engineering backbone concept for product development and lifecycle management in the context of the Industrial Internet and for integrated and interdisciplinary MBSE, product line engineering and service lifecycle engineering (Eigner, 2015a). Approaches like "Digital PLM" (Accenture, 2016) or "Bi-modal PLM/IT" (Gartner, 2016; Voskuil, 2016) reflect in a similar way like SysLM the need for evolution: from sequential to cross-linked, from document-based to model-based, from monolithic to federated and light weighted systems.

The proposed changes give rise to a number of requirements for future solutions. These encompass the range of solutions presented by an integrated SysLM strategy: (a) interdisciplinary, both in terms of the disciplines and throughout the product lifecycle (horizontal and vertical integration), (b) collaborative engineering between disciplines, throughout the product lifecycle, and along the supply chain, (c) system lifecycle mentality, with greater involvement of upstream and downstream processes and from monolithic to federated lightweight systems. Central drivers and core elements for designing an integrated SysLM strategy are the complete description of a product as a "digital (system) model", the instantiation of the digital model, innovative concepts for visualizing complex structures, and the integration of authoring systems in enterprise IT architecture.

## 3 ECO-SYSTEM AND ENTERPRISE INFORMATION MODEL FRAMEWORK

The evolution of virtual product modelling and model management based on the experience of the authors and the respective institute (Institute for Virtual Product Engineering (VPE), University of Kaiserslautern, Germany) can be set in a holistic context to illustrate past evolutionary changes and to derive potential areas of evolution and respective areas of research. In the following chapter a framework is introduced to provide this holistic context and "white spots" are framed.

### 3.1 Introduction of Framework

In order to structure and describe the evolution of virtual product modelling and model management a pragmatic framework was determined based on research work and industrial experience (Riemensperger, 2016). This framework has two axis describing the focus of the activities of companies and industries are addressing, in order to build-up and establish processes, methods and tools to support digitalization and new digital business models.

The axis **Internal Focus** addresses the "Digital Enterprise" with its mainly transactional processes along the supply chain with high priority on manufacturing processes. (Figure 2, a) In Europe and especially in Germany the priority on manufacturing can be seen in the industrial and political trend of "Industry 4.0". On the other axis the **External Focus** addresses the "Digital Customer" to enable market penetration by providing new "digital customer experiences". In the centre of the framework as a bridge and enabler for Digital Enterprise and Digital Customer, **the product** is positioned and represented by the "Digital Twin" - as virtual representation of a physical product in field operations.

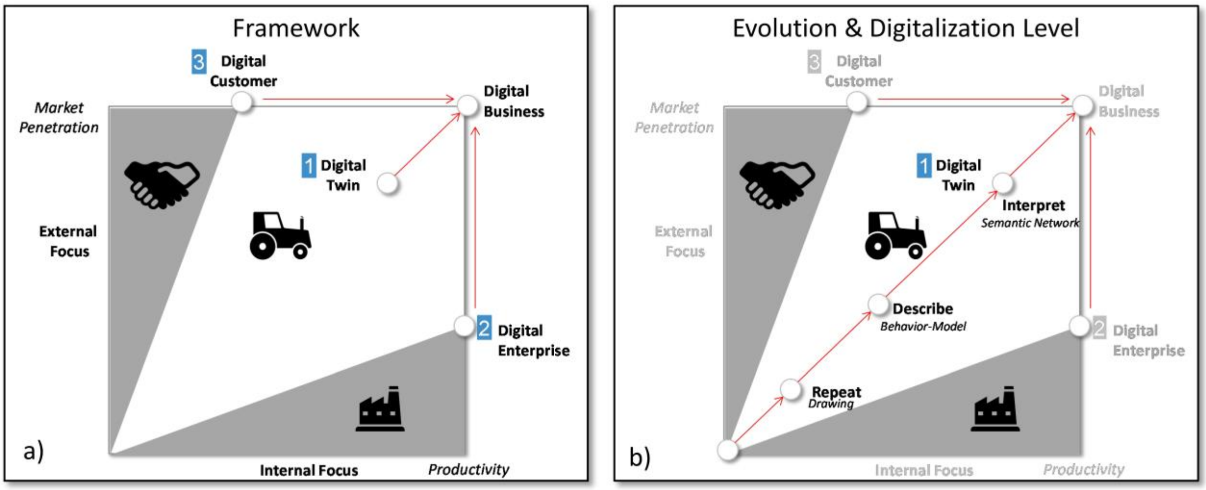


*Figure 2. Eco-System & Enterprise Information Model Framework*

Combining all three building-blocks, Digital Twin, Digital Enterprise and Digital Customer, the full potential of digitalization can be unleashed to support "Digital Business" with new business models.

### 3.2 Evolution Towards Digitized Engineering

With the focus on virtual product modelling and model management in this paper, the framework needs to be elaborated more in detail. The digital representation of a product evolved over the past years (Figure 2, b). In analogy of core capabilities in the linguistics three major steps of evolution can be elaborated:

- First step of evolution, the capability to **repeat the physical product** in a "virtual" way by a drawing or a 3D model. This level of maturity is characterized by the reflection of geometry for mechanics or schematics and layout plans for electrics/electronics.
- As a second step, the **physical product is described by its structure and behavior -** both product internal and external interaction with environment and customer. In research and industry approaches of modelling languages were defined and established: structure and behavior models (e.g. with UML, SysML).
- Third step of evolution is the ability to **trace, interpret and predict the product and its structure and behavior** in interaction with the environment and customer (the "meaning" of a product). Leveraging semantic networks help to reflect the product and its components in different scenarios, as product usage or product maintenance. Semantic networks can be found in communication technologies as World Wide Web (e.g. Resource Description Framework (RDF)). However, integration with product-related modelling across multiple engineering disciplines is not well defined or standardized (Conrad et al., 2007).

Derived from the field of linguistics, three digitalization levels were elaborated which reflect the ability of virtual product modelling and model management: **repeat ("low"), describe ("middle") and interpret ("high")**.

The framework introduced in this paper was used to depicture the evolution of experience of the VPE Institute, reflected by the respective research projects, with focus on product modelling as well as data and model management (see Figure 3). According to the described evolution - repeat (geometry), describe (behaviour), interpret (meaning) - modelling approaches as introduced in Chapter 2 (and in the following Chapter 4) can be mapped according to Figure 3. The position within the framework was defined in the context of preparation workshops of the authors and related experts. Nevertheless, the main intention is to provide a framework to position existing capabilities (up to digitalization level "middle") and to derive further need for research work (to achieve digitalization level "high").

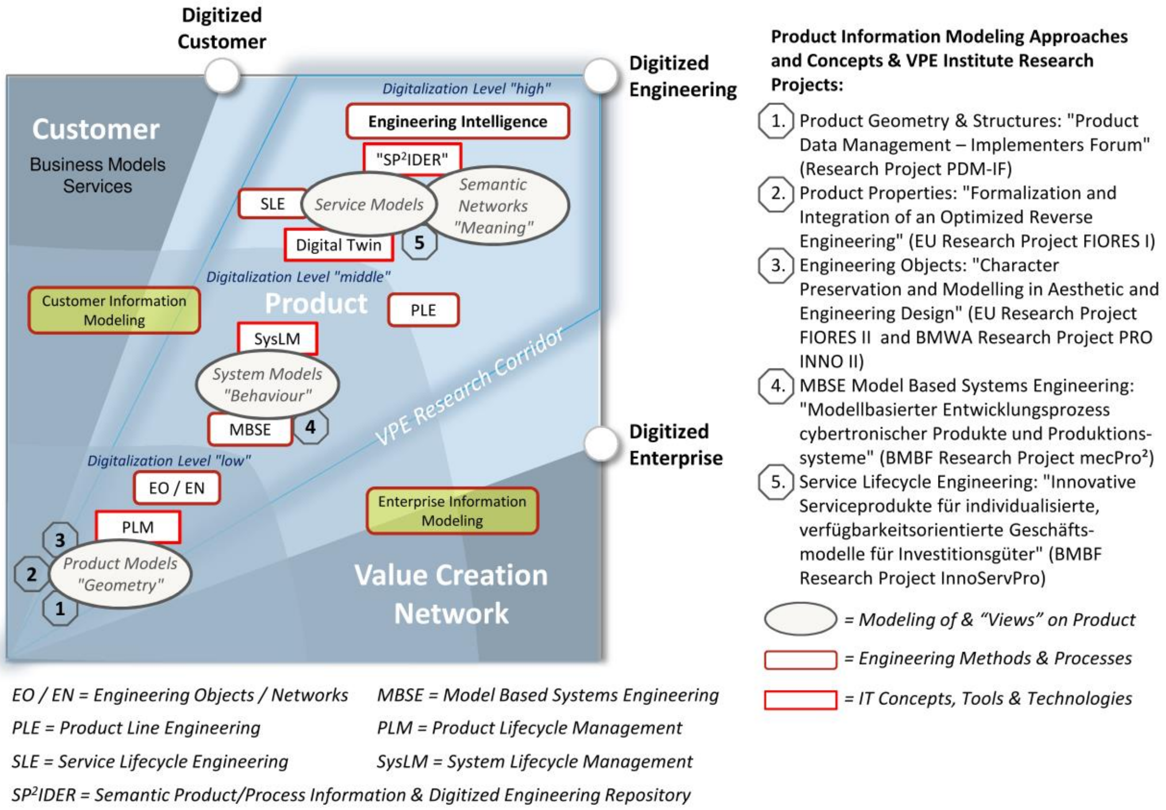


*Figure 3. Illustration of the evolution towards Digitized Engineering including VPE research projects*

### 3.3 Derivation of Further Research Work

Derived from the introduced framework and the mapping of respective product modelling approaches the third digitalization level "high" (interpret) within Figure 3 appears to be a field for further research work. Based on this understanding and industry experience two hypotheses can be formulated that need to be proven during further research work:

- Methods, processes and tools to perform product modelling (digitalization levels "low" and "middle") do exist per domain (e.g. Engineering vs. Manufacturing) along the product lifecycle ("vertical value chain integration").
- The integration of these domain-specific models combined with the ability to interpret and analyse (digitalization level "high") requires an integration layer on "Enterprise Level" ("horizontal value chain integration").

According to (Koch et al., 2017) Digitized Engineering and Industry 4.0 call for increased digitalization of horizontal and vertical value chains. Horizontal digitalization integrates and optimizes the flow of information and goods from the customer through their own company to the supplier and back. Vertical digitalization is used to ensure a continuous flow of information and data from sales through product development to production and logistics. Measuring the digitalization level of horizontal and vertical value chains allows determining the degree of "digital integration" of a company.

## 4 OVERVIEW OF CURRENT RESEARCH BASED ON THE FRAMEWORK

As a result and based on the framework from Chapter 3 several areas of evolution and respective areas of research have been developed and defined in the field of digitalization level "high". Some of them are already subject of current research work at VPE and will be described in the following.

### 4.1 Federated, Integrated and Interdisciplinary SysLM Backbone Concept

Today, the development of complex technical products and production systems involves the interaction of various disciplines of mechanical and electronics engineering and software development throughout the product lifecycle and along the supply chain. Digitalization, or the complete representation of a product in digital models, is a suitable approach for bringing together these disciplines in early development phases (Eigner, 2016). However, in current practice, the models of the various disciplines are often displayed in a variety of different and incompatible data formats that are distributed across different systems. As a result, the data from the authoring systems are organized by discipline in the PLM/ALM or PPS backbone, in some cases interconnected by a TDM layer (team data management). For tasks spanning the PEP this makes it more difficult to maintain an overview, because relevant data often need to be culled from the various systems. It is therefore preferable to be able to access all data without having to switch between different systems. For most companies, replacing the existing software landscape with an integrated total solution is not realistic.

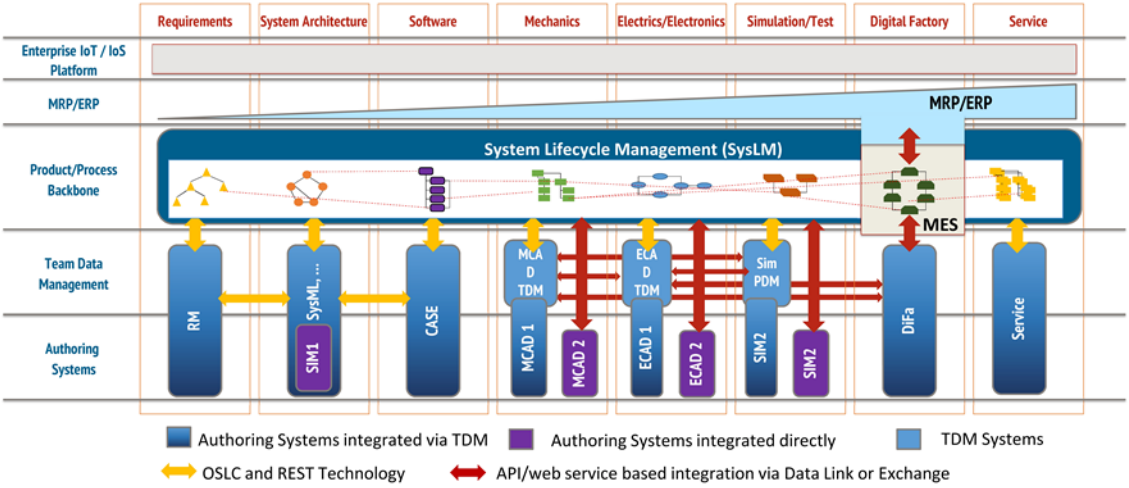


*Figure 4. Integrated backbone solution for System Lifecycle Management*

The concept of federated SysLM backbones offers an alternative. Here, a lightweight layer is laid over the existing systems (Figure 4) which stores references to objects in the different source systems. Access to those objects is managed via open standards like OSLC (Open Services for Lifecycle Collaboration). Apart from the technical challenges associated with the collection of data from the various systems, there is also the issue of how these data should be managed and visualized. While the data sets from the different systems provide views of the same product, their structures generally vary. For example, the engineering BOM (E-BOM) differs from the manufacturing BOM (M-BOM), not only in the objects represented, but also in the use of different numbering and the different grouping of data. This requires all objects from each system and their relationships to be mapped. A graph-based model (e.g. RDF triples) is suitable for storing these mappings. As an example for a federated SysLM backbone software solution the so-called SP²IDER (Semantic Product and Process Information & Digital Engineering Repository) system is currently being implemented at VPE. An earlier implementation of these ideas in context of Engineering Change Management is described in the following.

## 4.2 Change Management Backbone & Control (CMBC)

In order to show that a SysLM Backbone can simplify the complexities of engineering change management across different IT systems, the Change Management Backbone & Control (CMBC) demonstrator was programmed at VPE (Eigner et al., 2015b). To carry out a change process from beginning to end, information from all phases of the product development process is necessary, but this information is distributed and stored in different IT systems. For change management processes, collective data from all these systems have to be considered in order to recognize incompatibilities. Because of this complexity, an engineering backbone was installed over all data storage systems to integrate the data from the source systems. Figure 5 shows the different layers that compose the CMBC service. The lowest layer is the "link repository", which stores items that contain the information required to identify the item in its source system. The second layer of CMBC is the graph-based visualization. One advantage of the graph is its simplicity. Every element is a node, and every connection between two elements is an edge. If an element is present in multiple source systems, it is stored in CMBC as a node with references to each system. The topmost layer contains the change management web interface, which manages the change management process, starting with a problem report that identifies a need for change.

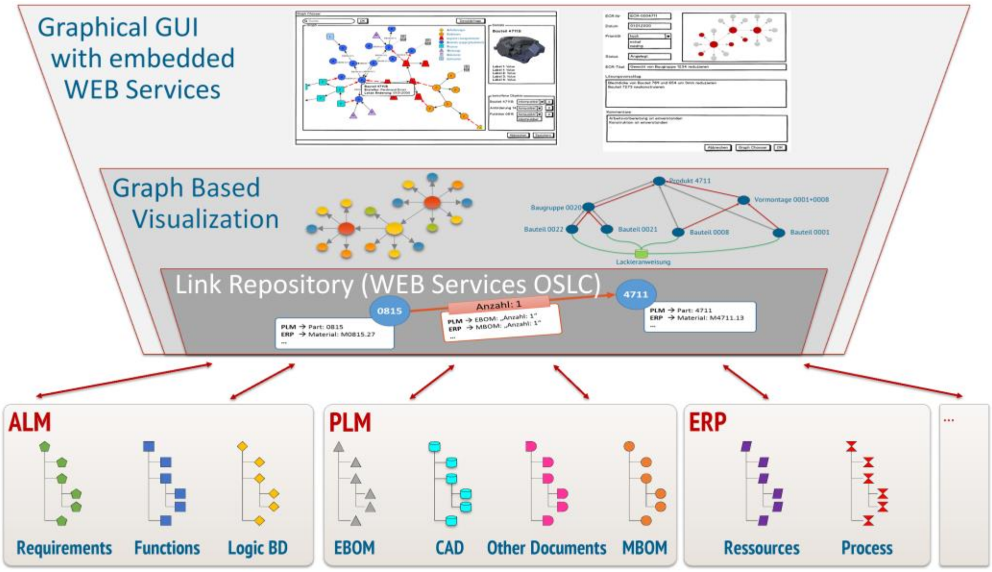


*Figure 5. Layers of the integrated CMBC model*

Alongside textual information, a graph systematically logs the "affected items", the elements affected by a change across all source systems. The system-wide approach makes it possible to detect changes more quickly and more comprehensively, and the graph allows for a very intuitive capturing process as well. In the future, the "digital twin" (see Chapter 4.5) could be used not only for logging changes in a non-product-specific way. It could also be tracked for one or more physical products via a link in the graph, because every "as-built" BOM, for example, is linked directly to the graph.

### 4.3 Product Line Engineering

Product Line Engineering (PLE) is defined as the engineering of a portfolio of different programs and of the varying products within it. The variability is intended to achieve substantial market coverage (external variance) at the lowest possible operating expense through a lower internal variance. Tools to keep the inner variability low include defined hardware and software interfaces or, in general, any transfer of the variability to the software. The term PLE originates from software engineering, but more recently it has been applied to the entire interdisciplinary product, program, and portfolio (ISO 26550 Reference Model for System and Software Product Line Engineering). The term is still relatively new in hardware development, but variants and modular systematics have been popular methods to optimize product development and production since the 1960s. The objective is to reduce development costs and time-to-market while increasing productivity, product scalability, and quality. PLE is subject of a doctoral thesis which is currently developed at VPE.

### 4.4 Service Lifecycle Engineering

The modern approaches of internet-based services that are offer communicating products often start from a mass data analysis during the production and operation phases. The design and implementation of these new service-oriented business models are referred to as Service Lifecycle Engineering (SLE). This means an extension of the digital model into the service sector and thus an extension of traditional PLM solutions (see Figure 1). It is interesting to identify which components and systems cause qualitative or functional problems for the optimization of the product development process (PDP). Through direct access to the technical master data in a SysLM solution, the designer can obtain information at any time on the frequency of errors or the status of a component. SLE is currently subject of research work done by VPE within the research project InnoServPro (InnoServPro, 2017).

### 4.5 Digital Model & Digital Twin

In the context of digitalization and Industrial Internet, the "digital twin" emerges as an important data structure. The digital twin is the computerized companion of an existing physical product. It comprises all data about a single instance of a product across its lifecycle. In the context of Industry 4.0, this is often referred to as an "administrative shell" (VDI, 2015). In contrast, the digital model contains all data about the product in general (e.g. classical PLM data). The digital twin also serves as a central anchor for all data produced by the product during its use (e.g. sensor data, maintenance reports). Until development and engineering tasks have been completed, all data is available as a 150% model containing the complete variation model. The individual variants are derived from this as 100% models in accordance with existing pre-established rules (e.g. by the customer during order process). Then, the model of an individual variant is executed e.g. by production. At the end of the process there is a physical product that is delivered to the customer. A digital twin can also be created when a 100% model is created ("as-built" BOM). This is an instantiation of non-order-related documents and represents a model for a physical product that is to be constructed. It is identifiable by a UID (unique identifier) and can be used, for example, to capture field data or update firmware. The digital twin brings together development, production and operating phases (Muggeo and Pfenning, 2016). The digital twin's level of abstraction depends both on the type of product in question (in terms of customizability and batch size) and on the current phase of the product's lifecycle. For example, in case of a simple product like a toothbrush it is sufficient to trace the product's MBOM during production. It is not necessary to store additional data during the product's use, because no maintenance is planned. For more complex products it is necessary to trace all service-relevant parts, as the twin must represent the product's current configuration at all times. The relevant information can be stored in the form of a versioned list (either hierarchical or flat) of a subset of the product's BOM (Figure 6). The individual elements of this structure don't have the full complexity of items in a PLM system (e.g. version info, CAD data), they just contain a link to the corresponding version of the element's representation in the digital model.

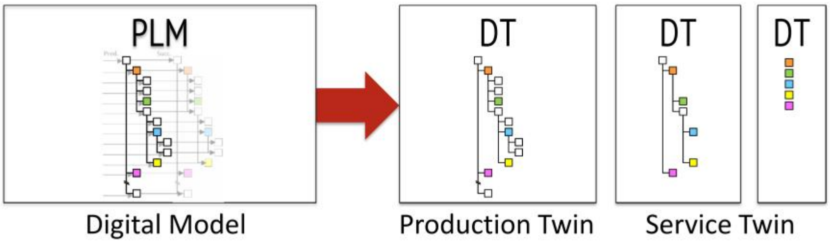


*Figure 6. Digital Model and Digital Twin (DT)*

The digital twin makes it possible to develop new business models. For example, machine availability can be sold instead of the machine itself. In this case, the digital twin conducts the monitoring of all machine functions and can trigger an alarm before important parts fail, so that timely maintenance can be performed (Muggeo and Pfenning, 2015). The digital twin has to display all of the changes that the physical product goes through ("as-maintained" BOM). This data could theoretically be stored in the product itself. However, data analysis across all instances of both the product and service processes triggered by data stored in the twin requires that the digital twin is available on the server side. A reasonable compromise can be achieved by storing a reduced version of the server-side twin on the device which is then regularly synched along with the collected field data. Research work on digital twin is currently done by VPE within the research project InnoServPro (InnoServPro, 2017).

## 5 CONCLUSION AND OUTLOOK

In the future, the focus will be on intelligently networked, communicating product systems, and thus on knowledge of the entire lifecycle of a product system operating in its eco-system. Managing the corresponding complex and networked information holistically across the lifecycle requires an interdisciplinary description based on an integrated system model in the early phases of the lifecycle and data capture across all lifecycle phases. The design of the Industrial Internet is the basis for accomplishing this. System Lifecycle Management is a core concept and potential engineering backbone for interdisciplinary product development and lifecycle management in the context of Industrial Internet.
Concerning evolution towards Digitized Engineering the authors see a new, future research area that they call "Engineering Intelligence": a new engineering design methodology going beyond "classic" ones in engineering design, combining methods and technologies of both business analytics and knowledge-based engineering. This will allow, on the one hand, analysis and interpretation of e.g. real-time field data or service information of a product by application of intelligent patterns and algorithms, and, on the other hand, "predictive modelling" in engineering design on the basis of knowledge models. As a result, e.g. new product services or improved product development processes could be possible with

improved integration, more re-use, better maintenance and more automation. Research work concerning "Engineering Intelligence" is currently done by VPE within the research project InnoServPro.

## REFERENCES


Accenture (2016), "Digital PLM - Reshape your innovation and product development". https://www.accenture.com/us-en/insight-digital-product-lifecycle-management

Bitzer, M., Vielhaber, M. (2013), "Technology Framework for Product Design". In: Smart Product Engineering. Proceedings of the 23rd CIRP Design Conference, Bochum, Germany, March 11th - 13th, 2013.

Conrad, J., Deubel, T., Köhler, C., Wank, S. and Weber, C. (2007), "Comparison of knowledge representation in PDM and by semantic networks". In: Proceedings: Int. Conference on Engineering Design, ICED07.

Dankwort, C.W., Eigner M., Faißt K. G., Keßler A. (2012), "Enhanced Object-Driven Design (EOD) based on Product Properties – Fundamentals and Implementation in the Engineering Network Concept", in Marjanovic, D., Storga, M., Pavkovic, N., Bojcetic, N. (eds) (2012), 12th International Design Conference DESIGN 2012, Dubrovnik, University of Zagreb, Croatia, pp. 421-434.

Deloitte (2016), "How technology is moving the automotive industry from products to relationships", https://www2.deloitte.com/content/dam/Deloitte/us/Documents/manufacturing/us-mfg-how-technology-is-moving-the-automotive-industry-from-products-to-relationships.pdf

Dyson Website (2017), http://www.dyson.com/community/aboutdyson.aspx (01.01.2017).

Eigner, M., Gilz, T., Zafirov, R. (2012), "Interdisziplinäre Produktentwicklung", Symposium Technisches Design 2012, TUDpress.

Eigner, M., Dickopf, T., Apostolov, H., Schäfer, P., Faißt, K.G., Keßler, A. (2014), "System Lifecycle Management - Initial Approach for a Sustainable Product Development Process Based on Methods of Model Based Systems Engineering". In: 11th IFIP WG 5.1 Int. Conference PLM 2014, pp. 287--300, Springer, Heidelberg (2014).

Eigner, M. (2015a), " Workshop - System Lifecycle Management", In: ProSTEP iViP Symposium 2015. https://www.uni-kl.de/fileadmin/erma/pdf/ProSTEP_iViP_Symposium_2015.pdf

Eigner, M., Eickhoff, T., Ernst, J., Eiden, A. (2015b), "Systemübergreifendes Änderungsmanagement zwischen PLM und ERP", in: "PLM IT Report", Jhrg. 2015, HeftNr. 5, Weka GmbH, Darmstadt 2015, S. 36-38. - ISSN: 0930-7117.

Eigner, M. (2016), "Das Industrial Internet." In: Sendler, U.: Industrie 4.0 grenzenlos. ISBN: 978-3-662-48277-3, pp.137-168, Springer, 2016.

Gartner (2016), "Bi-modal IT". http://www.gartner.com/it-glossary/bimodal/

INCOSE (2016a), "History of Systems Engineering". http://www.incose.org/AboutSE/history-of-systems-engineering

INCOSE (2016b), "Systems Engineering Standards", http://www.incose.org/AboutSE/SEStandards

InnoServPro (2017), "Innovative service products for individual, availability-oriented business models for capital goods", research project funded by BMBF, Germany. http://www.innoservpro.de/

Koch, V., Kuge, S., Geissbauer, R., Schrauf, S. (2017), "Industry 4.0 - Opportunities and Challenges of the Industrial Internet". http://www.pwc.de/en/digitale-transformation/pwc-studie-industrie-4-0-steht-vor-dem-durchbruch.html, 2017-04-24.

Mogo Nem, Fabrice (2011), "Engineering Networks: Holistic approach for multidisciplinary Product Lifecycle Management", Dissertation, in: Eigner, Martin (Hrsg.): "Technische Universität Kaiserslautern, Schriftenreihe VPE", Band 9, Kaiserslautern, 2011.

Muggeo, C., Pfenning, M. (2015), "Die Rolle von MBSE und PLM im Industrial Internet". In (Schulze, S.-O.; Muggeo, C., Eds.): Tag des Systems Engineering. Verteiltes Arbeiten mit ganzheitlicher Kontrolle. Hanser, 2016; pp. 279–288.

Muggeo, C.; Pfenning, M. (2016), "Die Durchgängigkeit des Engineering", in: "Computer & Automation - Fachmedium der Automatisierungstechnik", Jhrg. 2016, HeftNr. 3, Weka Fachmedien GmbH, Stuttgart 2016, S. 22-25. http://www.computer-automation.de/unternehmensebene/engineering/artikel/128218/

OMG (2016), "What is SysML?". http://www.omgsysml.org/what-is-sysml.htm

Riemensperger, F. (2016), "The Industrial Digital Transformation: It is all about Platforms, Agility and Speed", ProSTEP iViP Symposium 2016.

Scheer, A. (2015), "Industrie 4.0. 225–239. http://aws-institut.de/wp-content/uploads/2016/02/AWScheer_Whitepaper5_Industrie-4_0.pdf

VDI Verband Deutscher Ingenieure e.V. (2015), " VDI Statusreport. Referenzarchitekturmodell Industrie 4.0 (RAMI4.0)". https://www.vdi.de/fileadmin/user_upload/VDI-GMA_Statusreport_Referenzarchitekturmodell-Industrie40.pdf

Voskuil, J. (2016), "Bimodular" by Asell, J. at PDT Europe 2016, Paris. https://virtualdutchman.com/2016/11/13/the-weekend-after-pdt-europe-2016-paris-part-1/