



**HAL**  
open science

# Digitalization of the Engineering Supported by System Lifecycle Management (SysLM)

Martin Eigner, Mona Tafvizi Zavareh

► **To cite this version:**

Martin Eigner, Mona Tafvizi Zavareh. Digitalization of the Engineering Supported by System Lifecycle Management (SysLM). 18th IFIP International Conference on Product Lifecycle Management (PLM), Jul 2021, Curitiba, Brazil. pp.240-254, 10.1007/978-3-030-94399-8\_18 . hal-04195242

**HAL Id: hal-04195242**

**<https://inria.hal.science/hal-04195242v1>**

Submitted on 4 Sep 2023

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License



This document is the original author manuscript of a paper submitted to an IFIP conference proceedings or other IFIP publication by Springer Nature. As such, there may be some differences in the official published version of the paper. Such differences, if any, are usually due to reformatting during preparation for publication or minor corrections made by the author(s) during final proofreading of the publication manuscript.

# Digitalization of the Engineering supported by System Lifecycle Management (SysLM)

Martin Eigner<sup>1</sup>[0000-1111-2222-3333] and Mona Tafvizi Zavareh<sup>2</sup>[1111-2222-3333-4444]

Former Head of the <sup>1</sup>/ actual research associate at the <sup>2</sup>  
Institute for Virtual Product Engineering, University of Kaiserslautern  
Gottlieb-Daimler-Str. 44, Germany  
eigner.engineeringconsult@gmail.com  
tafvizi@mv.uni-kl.de

**Abstract.** This article explains the implementation of digitalization especially in the field of engineering. Digitalization, both of the product and the service developed within the framework of service-oriented business models, will be presented. Another key point of digitalization is the horizontal and vertical integration of technical and administrative work processes along the product life cycle. The vertical integrations are about the integrations of the authoring systems along the life cycle phases; requirements management, system architecture, CAD in mechanics, electronics, software development, simulation, testing, process planning and digital factory into the overall System Lifecycle Backbone (SysLM). Horizontal integration focuses on administrative functions such as release, change and configuration management over the entire product life cycle and the technical integration of the information generated in the individual product lifecycle phases. The distribution and orchestration of functions between SysLM, MES (Manufacturing Execution System) and MRP (Manufacturing Resource Planning) is particularly relevant here. The contribution is rounded off by a compilation of relevant process- and technology-related requirements for a SysLM solution as well as a presentation of a concept for determining the degree of digitalization in engineering (maturity determination).

**Keywords:** Digitalization of Engineering, Engineering 4.0, System Lifecycle Management, Model Based Systems Engineering, Maturity Level.

## 1 Digitalization of Engineering - Basics

Digitalization - is this a new buzzword? Older readers still know the term CIM from the 80s? "CIM<sup>1</sup> describes the integrated use of computer in all production-related operating areas. It includes the information technology interaction between CAD, CAP, CAM, CAQ and PPS. The aim is to achieve the integration of technical and

---

<sup>1</sup> CIM Computer Integrated Manufacturing

organizational functions for product engineering”<sup>2</sup>. Some may remember that the term disappeared from public debate as quickly as it emerged. For a variety of reasons, this vision reached its limits, so that many people considered it to have failed. Was the time not yet ripe, were the management overwhelmed or were there not yet the right IT tools? Nevertheless, with a precise interpretation of the definition, it was already a partial disfigurement of the process chain product development to production planning and production.

After the short CIM euphoria and the lean wave, Industry 4.0, IOT<sup>3</sup> and IOS<sup>4</sup> are once again gaining a strong significance for the digitalization and automation of business processes at a new stage of evolution. Significantly improved methodological approaches and powerful IT tools suddenly bring CIM's vision within reach 35 years later. However, the dimension of digitalization is much larger and more disruptive. It influences every industry, the entire value creation process from requirements to different development phases, simulation, production planning and production to operation and finally re-cycling. It refers to innovative products, systems and services, as well as to all business processes, customers, service providers and suppliers. The Internet of Things and Services (IOT/IOS) [1] and Industry 4.0 are the source of connected products, systems and services in the future. The share of electronics and software will continue to increase in this type of products and embedded services. Communicating products with each other over the Internet, is used by Cyberphysical [2, 9] and Cybertronic Systems [6]. The development of these new systems will have several consequences: interdisciplinary, regionally and organically distributed and integrated product development, a rethinking of today's construction methods, processes, IT solutions and organizational forms, as well as the research for end-to-end process chains, based on digital models in the requirements definition, system architecture, product development, simulation, production planning, production and service. A modern, interdisciplinary and system-oriented product engineering process (PEP) is required.

### 1.1 <sup>VPE</sup> System Development Methodology – Foundation for a new PEP

The <sup>VPE</sup> System Development Methodology defines a holistic and interdisciplinary PEP [5, 7]. It adopts and merges concepts of different interdisciplinary and discipline-specific development methodologies and adapts them to the requirements and boundary conditions of cybertronic products and systems [6]. Based on the definitions of a basic methodology according to Martin [10] and Estefan [8], the methodology consists of three main components (see Figure 1):

- The Model Based Virtual Product Engineering (MVPE) process model fits the context of the Internet of Things and interdisciplinary design.
- The Kaiserslautern System Concretization Model (KSCM) is positioned as a corresponding design method

---

<sup>2</sup> Definition AWF (Ausschuss für wirtschaftliche Fertigung, Committee for Economic Manufacturing 1985)

<sup>3</sup> IOT Internet of Things

<sup>4</sup> IOS Internet of Services

- At the tool level, a 5-level IT architecture concept based on an engineering backbone is proposed (Extended according to the 4-level VDA concept). Here SysLM is positioned.

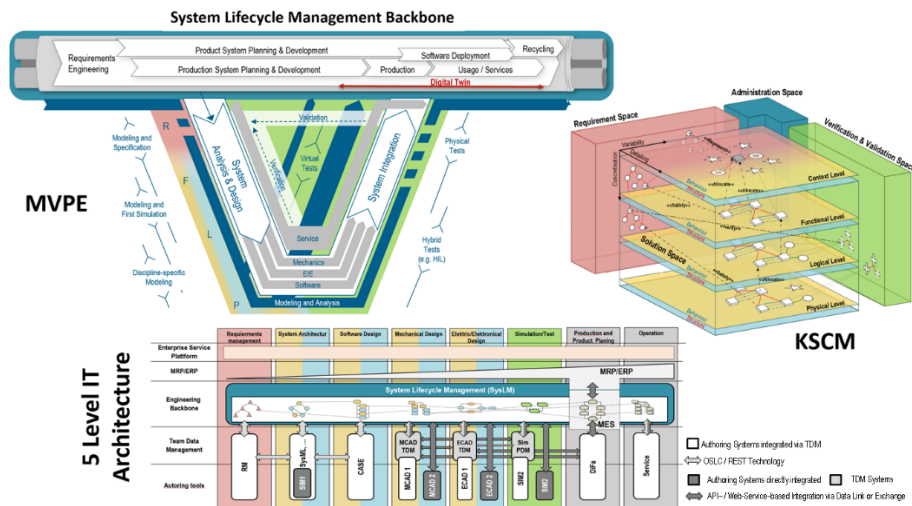


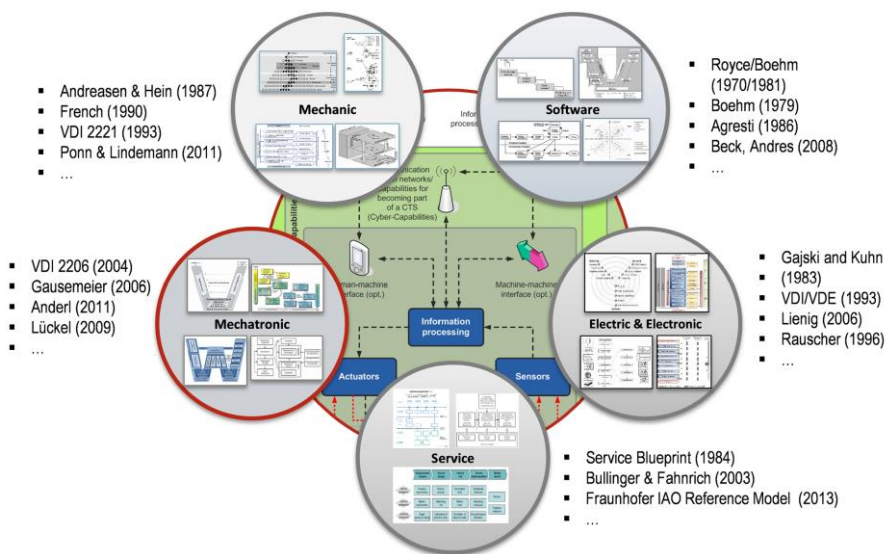
Fig. 1. : VPE System Development Methodology [5, 7]

While the MVPE model describes the general life cycle phases of a product or system development (process) with a specific focus on conceptual design and development, the KSCM bundles techniques to meet the tasks that arise in the phases of conceptual design and discipline-oriented development (method). The 5-step IT architecture concept describes a complementary approach to tool-based creation and management of system data over the entire lifecycle and the implementation of horizontal and vertical integration.

## 1.2 From silo-oriented thinking to an interdisciplinary system approach

Statistics from the last years prove the permanent transformation of the product engineering process (PEP). The influences result from changed market conditions, new requirements of the product, and the customer perspective. The increase in product complexity results on one hand from a considerably stronger ‘multi-market’ capable product, derivative and variant variety and, on the other, from the continuous increase of electronic components and the associated, ‘embedded software’ in the scope of the digitalization of products and services. The value proportion of electronics and software has increased continuously in recent years and, in vehicle construction, for example, it is at approx. 40 percent in value with an increasing tendency. New requirements for methods, processes, and process models for an interdisciplinary PEP are derived from this. This is based on organizationally and technically supporting the engineering product lifecycle, i.e., from the early phase of requirement, to development, simulation,

production planning, production and to operations, across all disciplines (→ mechanics, electrics/electronics, software, and services) and across all departments of a company. Today, there is still a lack of established, industrially used methods, processes, and procedure models for the cross-disciplinary development of products and systems. The development methods and processes developed in the various disciplines are completely different and led to inconsistent thinking, and working in discipline-oriented silos. Figure 2 shows an overview of an actual discipline-orientated education model based on different discipline-oriented and mechatronic – but mainly based on a mechanical background – design methodologies and approaches.



**Fig. 2.** Different Discipline-oriented procedure models in product development

The most important changes in the product and process world are on the one hand completely new requirements for products and production systems and service-oriented business models as well as new IT technologies, architectures and standards (OSLC/REST/RDF, web service, micro-services, multi-tenant databases, SaaS-Cloud) that enable the implementation of these requirements. The digitalization of products and product development means a transformation process that rearranges the classic boundaries of a fragmented and competing IT solution world. A lightweight and federated engineering backbone will play the role of data and process integration between product and production development, production/manufacturing and assembly, and service. In addition to the traditional PLM application, this central engineering backbone solution is called System Lifecycle Management (SysLM) [4, 6].

### 1.3 System Lifecycle Management (SysLM)

SysLM is an inter-disciplinary and holistic information and process management approach. It extends Product Lifecycle Management (PLM) with the early phases of system modelling, taking into consideration and integrating all disciplines, including services, in order to support production planning and thereby form bridges to production, as well as extend the operational phase of product operation. The concept is based on the intelligent direct and indirect integration (→ using TDM<sup>5</sup>) of various authoring systems along the entire Product Life Cycle (PLC) of a product, production system or the development of a service-orientated business model.

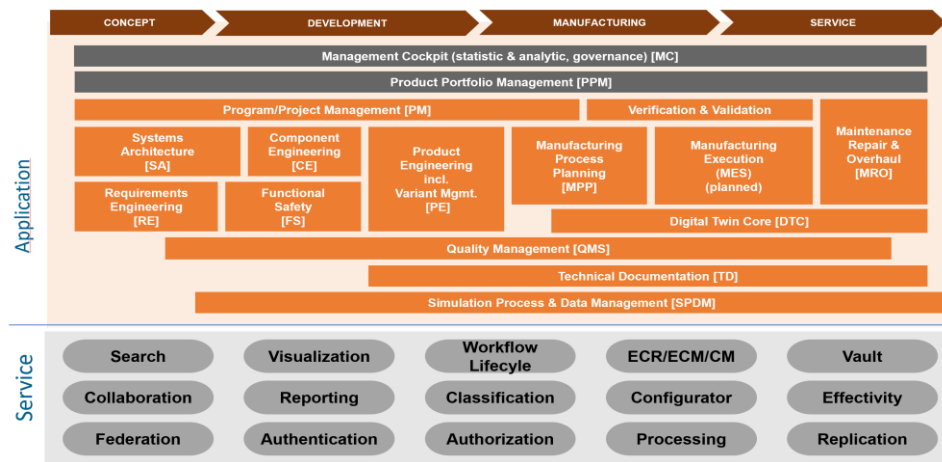


Fig. 3. Functional overview SysLM (source: according to Aras)<sup>6</sup>

As the technical-organizational backbone, System Lifecycle Management solutions are responsible for the horizontal integration of the partial models resulting in the phases of the PLC and for the provision of company-wide engineering processes (→ ECM<sup>7</sup>, CM<sup>8</sup>). These can be supported by Artificial intelligence (AI). This guarantees clear traceability (→ Digital Thread<sup>9</sup>, Digital Twin). In summary, SysLM extends the

<sup>5</sup> TDM Team Data Management administration systems closely coupled with authoring systems

<sup>6</sup> Effectivity in the PLM environment means when exactly a product with a defined part number and revision was produced

<sup>7</sup> ECM Engineering Change Management

<sup>8</sup> CM Configuration Management

<sup>9</sup> Digital Twin, Digital Model and Digital Thread: The Digital Twin (DT) represents products, processes, and services of the real world in the digital world. Stark et. al. [ 12 ] refer to it as the digital representation of a real product instance. The Digital Model is considered the backbone of Model Based Systems Engineering. It is formed from the individual partial models along the PLC and is based on formal or semiformal description languages. The Digital Thread describes the concept that links so-called Configuration Items along the PLC within the Digital Model as well as the DT.

PLM approach upstream (full integration of system modeling) and downstream (integration of engineering and production planning) and is based on modern WEB-based software technology. Model Based Systems Engineering (MBSE), System Thinking (ST), Advanced System Engineering (ASE) and SysLM can serve as a guideline for the mental transformation of silo-oriented thinking according to an interdisciplinary and system-technical engineering approach and the IT-technical implementation of Engineering 4.0. Figure 3 shows the typical functions of a SysLM system, sub-divided into application and service functionality.

## 2 Implementation of the Digitalization of Engineering

This chapter explains the implementation of the trends and methods of digitalization presented in the previous chapter, especially in the field of application of the engineering. The digitalization of both the product and the service products developed within the framework of service-oriented business models will be presented. Another key point of digitalization is the horizontal and vertical integration of technical and administrative engineering processes along the PLC (Figure 4).



**Fig. 4.** The Digitalization of Engineering / Engineering 4.0 [5, 13]

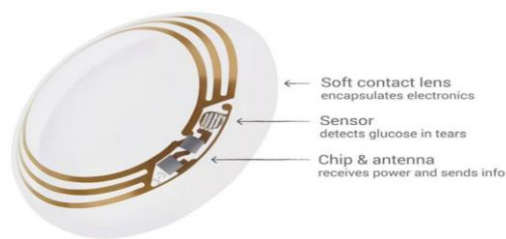
The vertical integrations are about the integrations of the authoring systems along the life cycle phases requirements management, system architecture, CAD in mechanics, electronics and CASE and simulation. Horizontal integration integrates the many phase-specific partial models and focuses on administrative functions such as ECM and CM throughout the production. In addition to the product and process-relevant criteria,



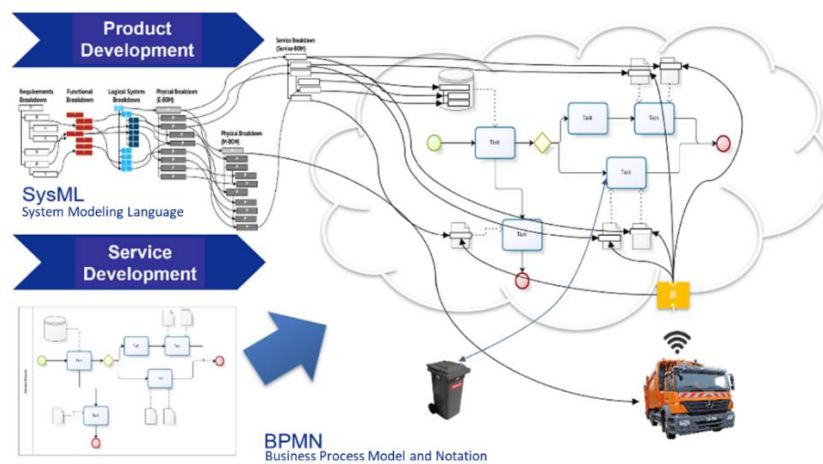
the digitalization strategy must involve the active and involved people, the corporate culture, the organizational structure and the current technologies. The chapter is rounded off with a requirements analysis of SysLM. The digitalization of production systems is not dealt with in this chapter due to the focus on the area of engineering.

## 2.1 Digitalization of Products and Services

As described in Chapter 1, IOT is based on networked and communicative systems and services based on them ( $\rightarrow$  IOS). The range of functions of current mechatronic systems is significantly expanded by mutual networking, interaction and interoperation. When they communicate with each other via the Internet, cyber physical systems (CPS) and cybertronic systems (CTS) are talked about. Both represent a further development of mechatronic systems in the direction of intelligence and communication skills. A one-time example of a Cybertronic product is Google's well-known contact lens (Figure 5). These intelligent types of products are also called Smart Product.



**Fig. 5.** The smart contact lens for measuring blood sugar (Source: Google)



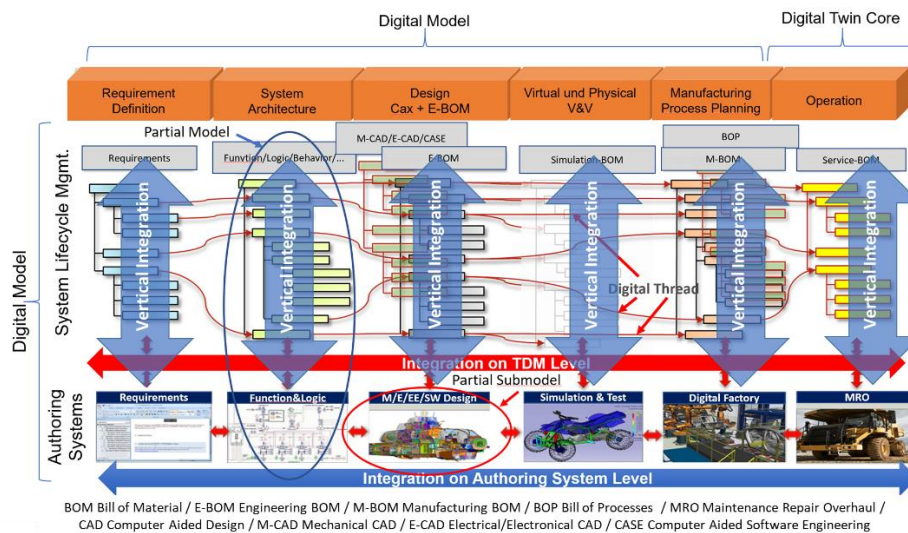
**Fig. 6.** Digital Models in a Full-Service System Garbage 4.0

On the basis of communicating 'things' ( $\rightarrow$  products/systems), new, often disruptive service-oriented business models are being built for various applications, i.e., Smart

Products, Smart Factory, Smart Energy, Smart Mobility, Smart Farming and Smart Buildings. Services within new overall systems are becoming the central success factor of the Internet of Service (IOS). A product can communicate and cooperate with another product systems in open networks, thus networking to intelligent, partly autonomous, self-adapting full-service systems. Figure 6 shows a research concept of optimizing the driving paths of a garbage truck by measuring the level of the garbage cans.

## 2.2 Digitalization of Engineering Processes

In addition to the digitalization of products, systems and services, the engineering processes must be digitalized too. The integration of the established technology of Product Lifecycle Management (PLM) and the newer technology of Model-Based Systems Engineering (MBSE) was recognized in its relevance for the implementation of Industry 4.0. It says: "The central themes here are PLM-supported engineering, which combines product and production design and enables end-to-end support across the entire value creation. This addresses technical points such as the integrated consideration of systems engineering, modelling and simulation"<sup>10</sup>. The digitalization of engineering processes is intended to understand not only the existence of life-cycle-specific IT solutions, but also the integration, i.e., the model-based handover, of information across IT systems. This use of models instead of documents is advantageous in development scenarios in which several disciplines are involved and the traceability of products is required due to international standards.



**Fig. 7.** Vertical Integration and Digitalization of Authoring Systems in TDM and SysLM along the PLC [5]

<sup>10</sup> German Platform Industry 4.0

Under vertical integration, the integration of authoring systems directly or via a TDM solution to a SysLM backbone and vice versa is to be presented here according to Figure 7. Especially the 'Up Stream' potentials, i.e., the system modelling and the integrated requirements modelling including the connection to the administrative level ( $\rightarrow$  SysLM) are still not used in industry today. The processes are not yet fully developed. But projects in this area are constantly increasing. The relevance of this integration in the early phase of the PLC is generally recognized by experts and will become increasingly established in the areas of high tech, automotive, medical, aerospace and defense in the next few years. On the other hand, the integration of M-CAD and E-CAD systems into TDM and PLM/SysLM has been standard for many years. Today, other rather little used areas of integration in industry are software development and simulation. These are typical fragmented and isolated application.

Each of the phase-specific partial models requires a specific data model when integrating with the SysLM backbone. As a typical example, the data model of software integration is shown here (Figure 8). Appropriate data models exist for Requirements, System Architecture, CAD for mechanic and electric/electronic and simulation.

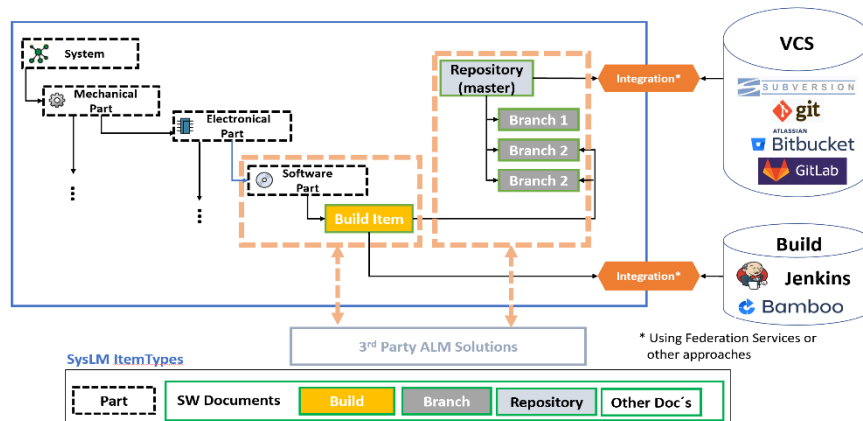
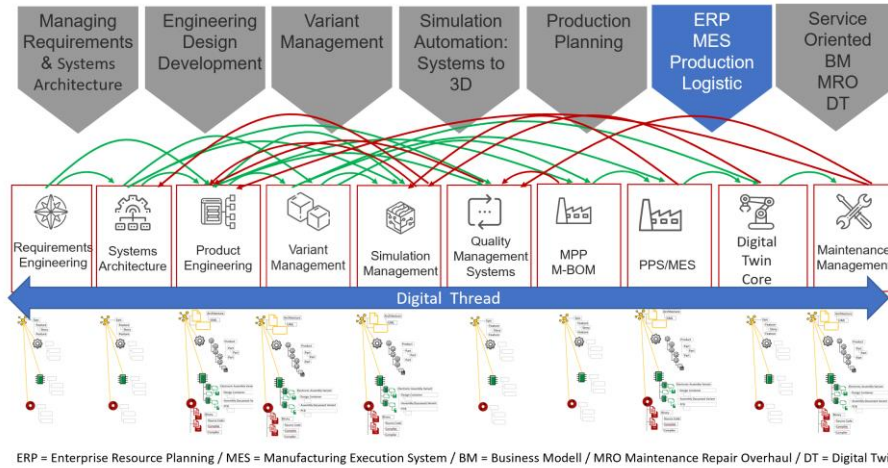


Fig. 8. Data Model for Software Integration in SysLM [5]

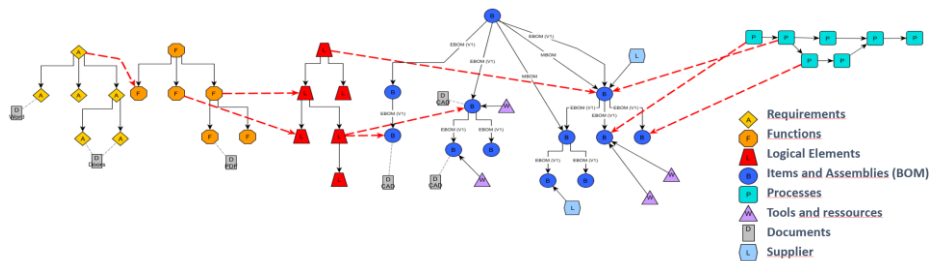
According to a study by Tech-Clarity, the cross-divisional integration of engineering is a major problem for nearly half of respondents. Thus, the central development areas work together, but not nearly enough, in order to achieve optimal innovative development results. Without consistent cooperation and interdisciplinary development methodology, it is hardly possible to develop innovative products and then implement changes to the product and in production consistently and in line with quality. The same applies to the tracking of claims. The digitalization concepts Digital Model, Digital Thread and Digital Twin are implemented in a SysLM system as an engineering backbone concept. Figure 9 shows the theoretical optimum of full horizontal integration. Vertical integration in the individual phases of the PLC must, of course, be implemented and the partial models must be connected and integrated. The arrows show the forward and backward information flow inside a SysLM solution.



ERP = Enterprise Resource Planning / MES = Manufacturing Execution System / BM = Business Modell / MRO Maintenance Repair Overhaul / DT = Digital Twin

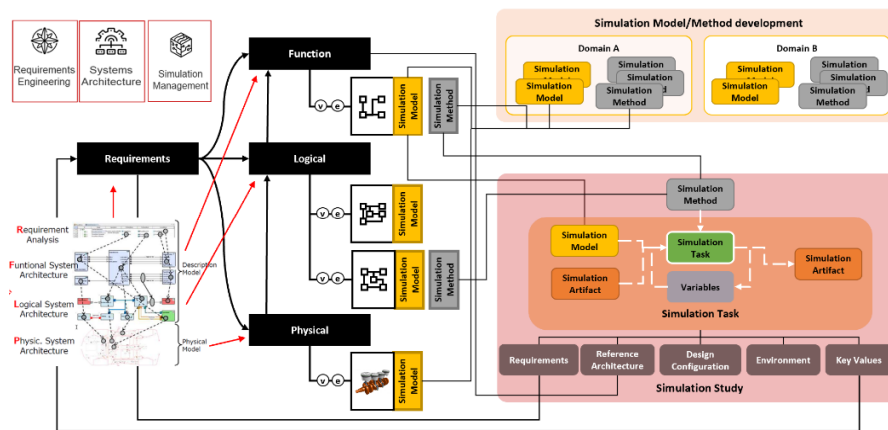
**Fig. 9.** Concept of implementing a horizontal integration concept [5]

The digitalization concepts Digital Model, Digital Thread, and Digital Twin are implemented in a SysLM system as an engineering backbone concept. Figure 10 documents the target of consistent and company-wide integration of the PLC phase with a simple example. In the event of a change to an individual engineering object, for example, a CAD document, all other potentially Configuration Items must automatically be found by the digital thread in the digital model across all phases of the PLC [11]. The more phases are integrated, the clearer and more complete is the statement resulting from this.



**Fig. 10.** Networking of all Configuration Items in the event of a change on the basis of a graph-based analysis across all object classes filed in SysLM

For horizontal integration, too, an example of a partial combination of requirements engineering, system architecture and simulation should illustrate the complexity of the data model (Figure 11).



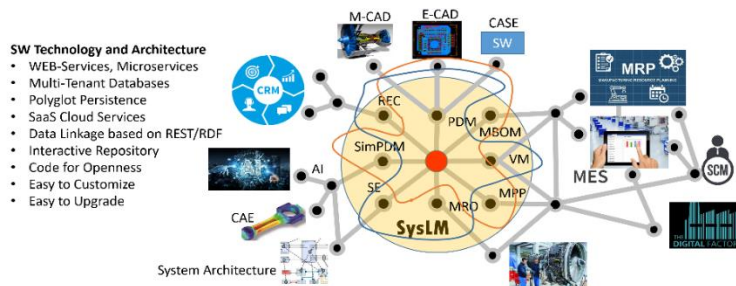
**Fig. 11.** Horizontal Integration of Requirements Engineering, System Architecture and Simulation [3]

### 2.3 Requirements for SysLM

The necessity for the functional extension to PLM was already mentioned in Chapter 1.3. Significant prerequisites of the digitalization of the products and services as well as of the vertical and horizontal integration of the engineering processes are [5]:

- Interdisciplinarity leads to stronger requirements for quality and traceability
  - In the scope of service-oriented business models, the operations of the product are increasingly in focus (→ digital twin, digital thread, and big data analytics).
  - Embedded software and electronics partly have more than 50% of the value of a product with an increasing tendency.
  - The high interdisciplinary nature leads to an obligation to guarantee quality, traceability, and the functional security within the product lifecycle.
- Modern Engineering Processes
  - Validation and verification through simulation and virtual testing must be orchestrated and administrated on the TDM level (→ SimPDM) and the engineering backbone level.
  - The increasing interdisciplinary product and system development requires new processes, methods and adapted IT tools for these for the engineering. MBSE, System Thinking, and agile processes gain a strategic importance for the digitalization and optimization of the engineering
  - Development is increasingly distributed and must be supported accordingly using the modern federation techniques of SysLM.
- New Application Functions

- Development and production planning will grow closer together. The redundancy between an E-BOM, an M-BOM and the BOP will be intelligently triggered.
  - Engineering processes (release, change, and configuration) will cover all disciplines, all phases of the PLC and, the supply chain.
  - Authoring systems are becoming more and more intelligent, and customers require new capabilities in integration, for example, the integration of new, lightweight and intelligent visualizations (→ dynamic/shattered view), VR<sup>11</sup> and AR<sup>12</sup>, more generative design technologies and electronic design automation (EDA) under the direct integration of simulation, AI and 3D-Printing.
  - AI and reinforcement learning will play a major role in the future.
  - SysLM must become the central management dashboard in order to manage and control the engineering processes (→ statistics & analytics, governance).
- Software Technology
    - The objective is: a farewell to the monolithic aircraft carrier to the federated, flexible frigate-based SysLM solution on modern technology and architecture.
    - An open question is the architecture: central core with distributed and linked applications, total decentralized with multiple cores or a hybrid solution? The favorite solution is documented in Figure 12.
    - In order to obtain elastic scaling (→ vertical and horizontal) and therefore performance and optimum deployment, further software technologies are required (→ microservices, containering, convergent and hyper-convergent systems). Microservices architectures are the foundation for the development of digital workloads and future system landscapes.



**Fig. 12.** Figure 12: Scalable hybrid SysLM solution

- When Cloud starts to become important SysLM provider has to switch from single-tenant SaaS environments. This temporary solution was not sufficient for elasticity, scaling and load balancing of the SysLM solution. Multi-tenant architecture is a foundation of all global web applications – Facebook, Twitter, Google.

<sup>11</sup> VR Virtual Reality

<sup>12</sup> AR Augmented Reality

- In order to obtain elastic scaling (→ vertical and horizontal) and therefore performance and optimum deployment, further software technologies are required (→ microservices, containering, convergent and hyper-convergent systems). Microservices architectures are the foundation for the development of digital workloads and future system landscapes.
- When Cloud starts to become important SysLM provider has to switch from single-tenant SaaS environments. This temporary solution was not sufficient for elasticity, scaling and load balancing of the SysLM solution. Multi-tenant architecture is a foundation of all global web applications – Facebook, Twitter, Google.
- There are SysLM functions, for example, visualizations, evaluations, in which parallel NonSQL databases, for example graph DBs (→ polyglot DB's) are better than SQL databases. Time series databases are specifically developed for the monitoring of mass data from measure values from feedback from sensors in a case of a -oriented business model.

### **3 Exemplarily Execution of Engineering Digitalization Maturity Determination**

The following section presents part of a maturity assessment tool conceived for digitalized engineering in the areas of horizontal and vertical integration. As discussed earlier in this paper, these areas can be seen as a frontline of digitalization in engineering, where, as in other fields of action (digitalized products and services as well as organization structure and culture, human resources and the usage of data and IT technologies), current and future market needs and the associated product and process requirements must be met and assessed [13]. Figure 13 shows a subset of the vertical integration matrix listing more common engineering applications. In this matrix the existence of the respective solutions and their degree of integration to the TDM, SysLM are queried. Within each maturity group the weighted arithmetic mean is also calculated in order to consider individual preferences. The highest level (evaluated for 3) is regarded for fully integration into the SysLM backbone. In the second matrix (Figure 13) the horizontal integration and coupling of processes and data between the PLC phases is focused, as covered in chapter 2.2. Data and information existing in each partial model is to be connected and used for all its previous and succeeding phases. The horizontal integration evaluation matrix is to be filled out with scores for connection of PLCs.

Further dimensions for evaluation of Personnel Development, Organizational Culture, Organizational Structure, Data Handling, Methods and Technologies are also designed as questionnaires. Based on a comprehensive maturity assessment, potentials for engineering digitalization can be identified on the basis of which a strategy or an individual roadmap can be developed. In order to be able to carry out a targeted maturity assessment, fundamental company characteristics such as company size, business sector, market segment, organizational structures and existing strategies must be also recorded. The maturity of the individual competencies and skills should be determined, which can take place, for example, through surveys and interviews of employees.

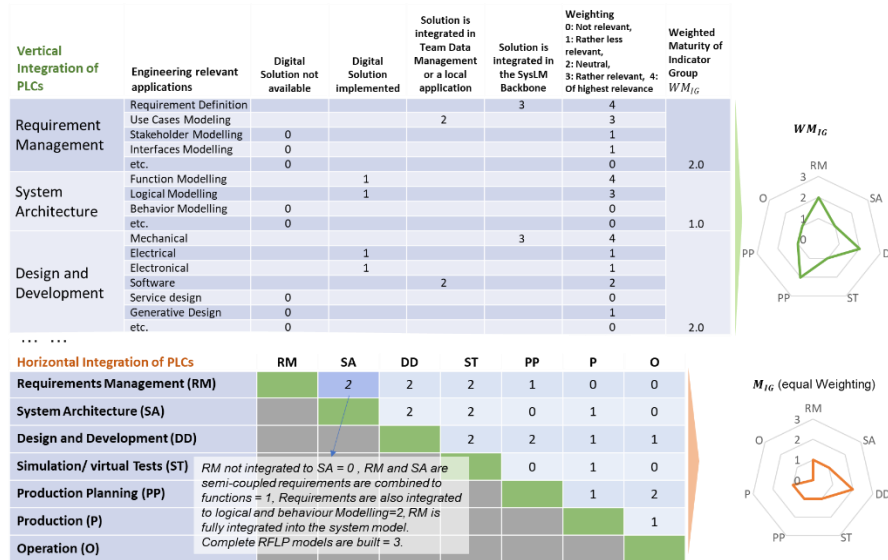


Fig. 13. Segments of vertical and horizontal Integration Matrices within a maturity model conceived for assessment of digitalization of engineering [13].

## 4 Summary

The development of innovative, mechatronic and cybertronic products, systems and connected services will lead to changes in several areas of the company. All areas are affected by this, however in particular product development, production planning, production, logistics and service. For operational implementation, the planning and design methodologies of all disciplines and all functional and operational units must be put to the test. The aim is to transform this to a common, integrated, and inter-disciplinary design process and IT solution approach (→ Engineering 4.0). New thought approaches of model based system engineering and system thinking form the basis, which force interdisciplinarity, digitalization and cooperation within the company and along the supply chain. The digitalization of products, services, and engineering processes introduces an important transformation process. It re-arranges the classic borders of a fragmented and competitive work and IT solution world. Here, a standard, light-weight, and federated engineering backbone on the basis of SysLM takes on the role of data and process integration along the PLC. Characteristics of SysLM systems are functions which, in connection and optimum orchestration with MRP and MES systems, fully integrate the engineering and production processes along the PLC on the basis of digital models, the digital thread, and digital twin. In the operating phase of the product, the digital twin supports service-oriented business models. These changes are only possible through new IT technologies. Here in particular, major drivers are artificial intelligence, big data analytics, intelligent generative CAD systems with optimization for 3D printing, linked data on the basis of REST/ RDF, new communication and database



technologies and architectures as well as the cloud technologies containing optimized, scalable application systems.

## References

1. Ashton K (2009) That ‘internet of things’ thing. *RFID journal* 22:97–114
2. Broy M, Cengarle MV, Geisberger E (2012) Cyber-Physical Systems: Imminent Challenges. In: Calinescu R, Garlan D (eds) *Large-Scale Complex IT Systems. Development, Operation and Management*. Springer Berlin Heidelberg, Berlin, Heidelberg, pp 1–28
3. Chądzyński PZ, Panthaki M, Nicolich M et al. (2020) Pervasive Simulation in a PLM Platform – The key to effective management of ever-increasing product complexity. *INCOSE International Symposium* 30:515–529. doi: 10.1002/j.2334-5837.2020.00737.x
4. Eigner M (2014) Modellbasierte Virtuelle Produktentwicklung auf einer Plattform für System Lifecycle Management. In: Sandler U (ed) *Industrie 4.0. Beherrschung der industriellen Komplexität mit SysLM*. Springer Vieweg, Berlin, Heidelberg, pp 91–110
5. Eigner M (2021) *System Lifecycle Management. Digitalization of Engineering*. Springer Vieweg, Berlin
6. Eigner M, Koch W, Muggeo C (eds) (2017) *Modellbasierter Entwicklungsprozess cybertronischer Systeme. Der PLM-unterstützte Referenzentwicklungsprozess für Produkte und Produktionssysteme*. Springer Vieweg, Berlin
7. Eigner M, Dickopf T, Apostolov H (2019) *Interdisziplinäre Konstruktionsmethoden und -prozesse zur Entwicklung cybertronischer Produkte. Teil 2. Konstruktion*
8. Estefan JA (2008) Survey of Model-Based Systems Engineering (MBSE) Methodologies. [http://www.omgsysml.org/MBSE\\_Methodology\\_Survey\\_RevB.pdf](http://www.omgsysml.org/MBSE_Methodology_Survey_RevB.pdf)
9. Gill H (2008) A continuing vision: Cyber-physical systems. In: *Fourth Annual Carnegie Mellon Conference on the Electricity Industry*
10. Martin JN (1997) *Systems engineering guidebook. A process for developing systems and products*. Systems engineering series. CRC Press, Boca Raton
11. Singh V, Willcox KE (2018) Engineering Design with Digital Thread. *AIAA Journal* 56:4515–4528. doi: 10.2514/1.J057255
12. Stark R, Thoben K-D, Gerhard D et al. (2020) WiGeP-Positionspapier: „Digitaler Zwilling“. *ZWF* 115:47–50. doi: 10.3139/104.112311
13. Tafvizi Zavareh M, Eigner M (2021) Determination of Engineering Digitalization Maturity. accepted for publishing. In: *Proceedings of International Conference on Engineering Design (ICED21)*, Gothenburg, Sweden