Chapter 1
Introduction to the Multi-Disciplinary Engineering for Cyber-Physical Production Systems

Stefan Biffl, Detlef Gerhard, and Arndt Lüder

Abstract The *Internet of Things and Services* opens new perspectives for goods and value-added services in various industrial sectors. Engineering of industrial products and of industrial production systems is a multi-disciplinary, model- and data-driven engineering process, which involves engineers coming from several engineering disciplines. These engineering disciplines exploit a variety of engineering tools and information processing systems. This book discusses challenges and solutions for the required information processing and management capabilities within the context of multi-disciplinary engineering of production systems. The authors consider methods, architectures, and technologies applicable in use cases according to the viewpoints of product engineering and production system engineering, and regarding the triangle of (1) the product to be produced by (2) a production process executed on (3) a production system resource.

This chapter motivates the need for better approaches to *multi-disciplinary engineering* (MDE) for *cyber-physical production systems* (CPPS) and provides background information for non-experts to explain the interaction between production engineering, production systems engineering, and enabling contributions from informatics. Furthermore, the chapter introduces a set of research questions and provides an overview on the book structure, chapter contributions, and benefits to the target audiences.

Keywords Multi-disciplinary engineering • Cyber-physical production systems • Product lifecycle management • Make-to-order • Model-based systems engineering

S. Biffl (✉) • D. Gerhard
Technische Universität Wien, Wien, Austria
e-mail: Stefan.Biffl@tuwien.ac.at; Detlef.Gerhard@tuwien.ac.at

A. Lüder
Otto-von-Guericke Universität Magdeburg, Magdeburg, Germany
e-mail: Arndt.Lueder@ovgu.de

S. Biffl et al. (eds.), *Multi-Disciplinary Engineering for Cyber-Physical Production Systems*, DOI 10.1007/978-3-319-56345-9_1

1.1 Motivation

Designing and developing smart products and systems comprising embedded systems and *Internet of Things* (IoT) technology—often referred to as *Cyber-Physical Systems* (CPS)—requires the extensive collaboration of several engineering disciplines. Product creation processes embrace engineering processes of the definition of products (or modules/systems) and of the required production system. This book essentially deals with the challenges of domain-spanning engineering processes of complex technical systems in the production area. This particular focus is mirrored in the term *Cyber-Physical Production System* (CPPS), which is also used in the title of this book. CPPS depicts the projection of the CPS concept to the production domain. Nonetheless, CPPS with emphasis on smart products, smart production, and product service systems have several links to CPS concepts focusing on other domains, e.g., “smart grid” in the energy domain and “smart mobility” in the mobility domain.

Within engineering processes for CPPS, several software solutions are used for different tasks in the sense of *Model-Based Systems Engineering* (MBSE). These engineering processes lead to many different but linked models, which have to be managed and maintained. To achieve this goal, typically several types of business information systems, e.g., *Product Data Management* (PDM), *Enterprise Resource Planning* (ERP), and *Manufacturing Execution Systems* (MES), form a company-specific *Product Lifecycle Management* (PLM) solution. The more complex engineering projects and associated models get, the more emphasis has to be put on interoperability and the ability to capture of the semantics of data in interfacing different systems.

This chapter introduces key characteristics of smart product design and production system engineering and derives requirements for informatics approaches that facilitate information modelling and data integration as foundation for multi-disciplinary engineering of CPPS.

The world of manufactured products, industrial goods, and services with associated businesses is changing its face. On the one hand side, there is *demand pull*. Drivers for this effect are manifold. New technical solutions are one approach to solve existing problems of the twenty-first century—often referred to as mega challenges—on a global scale. Examples are global warming, fresh water or energy shortage, and population growth. Tackling these challenges often leads to concepts, which require an increase of cost or resource efficiency, while high quality standards have to be maintained. In consequence, the complex and interconnected challenges result in complex technical systems with advanced information technology required to make them “smart”. Additionally, and sometimes in contrast to the stated global challenges, huge portions of the world are living in an unprecedented wealth. This also leads to steadily growing demands in terms of high-end consumer products, mobility and transport solutions, smart homes etc. Particularly, the demand for individualized products has increased and the lifecycle of products has shortened significantly.

In the early 1990s, car manufacturers had about 3–10 different models. 25 years later, they have a huge variety of models, crossovers, and derivatives easily exceeding 50–70 major variants. The development time of a car including production system has shrunk from 6 years to 2–3 years within the same time span. The sales lifecycle duration of a car was in some cases 30 years or more and is now about 8 years on average. In the consumer electronics industry, this effect is even stronger. Once a new smart phone is on the market, the predecessor does not sell any more, and the time span is not even 1 year. Sometimes, there is even an artificially generated customer demand, which cannot be explained by rational means, but western economies heavily rely on growth, and marketing experts do their best in generating demands.

These effects have a huge impact on industrial production. Production systems have to be quickly established in parallel to product development and furthermore, agile and flexible in order to be able to respond rapidly to changed production demands and variants. There is a strong demand to transform mass production to “lot-size-one” production while—at the same time—maintaining high quality and low production cost.

On the other hand—besides *demand pull*—there is a strong *technology push*. This has an impact on the products themselves but also on the production system. Besides the progress in production technologies enabling producers to exploit improved production processes, there is progress in automation and control technology based on information processing. Recent developments in PC-based technologies make it much cheaper to integrate intelligence into production system components enabling new control system architectures and new ways of control decision taking (Vogel-Heuser et al. 2013). For instance, condition monitoring of a machine tool or production system offers the option to perform preventive maintenance tasks and thereby reduce downtime or repair costs.

Together, these drivers lead to more complex production systems, see Fig. 1.1. This complexity has to be faced within both engineering and use of production systems as well as products produced within them. To do so, engineers have developed methods and tools like mechatronical engineering, agile programming, and plug-and-play of devices assisting them in dealing with system complexity and in dealing with the necessary quality of the engineering results.

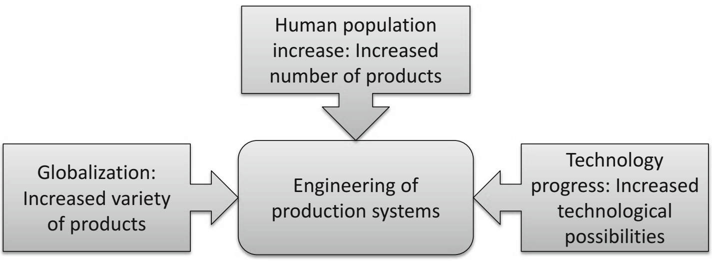

Fig. 1.1 Impact factors on production system engineering

One the one hand, we now face several engineering disciplines developed to enable the best possible engineering of a part of the overall production system. Initially in the 1950s, the engineering disciplines mainly were mechanical and electrical engineering, we now see on the one hand specialized disciplines emerging from the named two, such as multi-body simulation, computational fluid dynamics, tribology, or material sciences coming from mechanical engineering, and wiring, enclosure design, or communication system engineering coming from electrical engineering. In addition, we have seen emerge several new disciplines like control programming for *programmable logic controllers* (PLCs) and robots or optical system engineering (for laser-based welding). All of these disciplines have developed their special engineering methods, models, and terminologies applied within, and special tools to be used.

On the other hand, we see engineering process chains increasing in duration, complexity of the engineered technical system, and complexity of the required discipline-related skills, knowledge and activities. For example, engineering of a bodywork line for a car manufacturer contains around 25 engineering steps, which are executed by 25 different engineering tools. Well-known engineering activities are mechanical engineering design, electrical wiring design, and control programming. However, there are also less-known engineering steps, such as reachability analysis for welding points. All these engineering steps depend on each other's results. These dependencies form a tightly knit network. For example, the reachability analysis for welding points depends on the engineering design of the welding cell and the selection of a welding gun. In turn, the results of the reachability analysis for welding points have an impact on the engineering design of the welding cell and the welding gun selection.

Most of the engineering-discipline-specific tools have been enriched and detailed to engineering tools for the special engineering activities to be executed. Thereby, engineering-step-related dialects of the engineering methods, models and terminologies have emerged.

Engineering of production systems is conducted today in a multi-domain, multi-model, and multi-method environment, with a multitude of organizational, technical, and social dependencies. There are some initial works to analyze and optimize the raised complex engineering organizations, e.g., the VDI Guideline 3695 (VDI 3695 2009). However, the editors of this book are convinced that the improvement of production system engineering requires detailed knowledge about the boundary conditions of the engineering. These boundary conditions include possibilities of upcoming cyber-physical structures of production systems and (enforced by them) new possibilities of data and knowledge acquisition, integration, consistency evaluation, and management within collaborative multi-discipline and multi-model engineering.

CPPS is a very general term. In order to derive the research needs and challenges for CPPS engineering, it is necessary to distinguish different product types, production concepts, and production types. In the first place, four production concepts, reflecting the procedure during order processing, can be differentiated (Higgins et al. 1996): *Make-to-Stock* (MTS), or alternatively *Pick-to-Order* (PTO), reflects on production concepts for standard products without variants, which takes place independent of customer requests and orders, e.g. consumer electronics, hand machining tools, household appliances. *Assemble-to-Order* (ATO), or *Build-to-Order* (BTO), reflects on preproduction of standard products with manufacturer-specific variants irrespective of the order but connected to a customer-specific final production or assembly, e.g. cars and or personal computers. *Make-to-Order* (MTO) depicts production of standard products with customer-specific variants that are partly composed of pre-defined components and partly made up of only pre-designed components like gas turbines, airplanes, or kitchen furniture. Accordingly, new components are also created in this concept. Examples are complex machines for special products, machining tools or utility vehicles. With the *Engineer-to-Order* (ETO) concept, products according to customer specifications are produced, e.g. plant construction or shipbuilding. Because of specialization and considerable number of new components that have to be designed specific to an order, those products cannot be completely pre-engineered. A key characteristic of MTO and ETO production is the combination of existing standard parts with the new or adapted design of individual parts.

MTS products are typically produced in larger volumes (series or mass production) using a specialized production system. Those production systems have a special engineering process, which starts at a certain maturity level of the product. Largely they are optimized, often in a clocked flow production. Adaptability and re-configurability are not main concerns in terms of linking product engineering with production system engineering. ETO products are in general fixed site fabrications with job shop pre-manufacturing of single parts or pre-assemblies. Since there are only single items or small batches to be produced, there is no special engineering of the production system, but individual workshop production on standard *numeric control* (NC) machining tools. Furthermore, intra-logistics and material handling is in general not automated. The trend towards individualized products with customer specific requirements is moving industry away from MTS and mass production towards ATO or MTO in order to meet customer demands. ATO and MTO are often considered as sub-classes of *Configure-to-Order* (CTO). Configuration of products is the essential part of the order process prior to manufacturing and assembly. Typically, the components of the product cannot be chosen independently, i.e., dependencies have to considered. However, in ATO production, the dependencies are rather simple in nature; components of the product are defined in detail and may be prefabricated in stock. In MTO production, the dependencies are more complex compared to ATO, components are manufactured as needed. This requires additional flexibility in the production process, particularly in terms of detailed production and material flow planning.

These types of production processes are mainly addressed with CPPS approaches. Additionally, a far greater collaboration of product engineering and production system engineering as well as integration of the respective IT systems is required. A high degree of flexibility for variant rich and customized products requires the adjustment product structures accordingly. This leads to higher efforts for product modularization and product line definition. A thoughtful product structure is the necessary basis of the often referred to products that control their own production. The essential task of optimization in production is to increase efficiency in terms of four each opposing target dimensions: variability, quality, speed, and economy. This applies especially for CPPS approaches.

1.2 Background

Within the prior section, production systems have been named as product of the ETO approach. In the following, the distinction between product and production system will be clarified.

Technical systems are often distinguished in product and production system. In (Stark 2015), a product is characterized as the reason a company exists for, i.e. it is created and applied within the company business making profit by selling the product. Products can be tangible like cars and cameras or intangible like a repair service for cars or a print service for photos. The combination of tangible products and associated services is referred to as *Product Service System* (PSS). In contrast, production systems are seen by the different authors in (El Maraghy 2009) as a means to create products by appropriate combination of production factors. Production factors exploited are among others materials, used work-in-progress, applied production resources (machines), and the human workers executing the activities. As easily visible, the same object, for example a bakery, can be regarded as product (by the bakery system integrator) and as a production system for cake production (by the bakery owner).

Nevertheless, there are strong dependencies between product and production system. On the on hand, the product requires a production system to be created. The production system defines boundary conditions to the properties of products possibly to be created within. On the other hand, products define requirements to the production system able to produce them. For example within production systems of optical components of cameras, dedicated cleanness conditions have to be fulfilled. Hence, within the engineering of a production system, requirements coming from the products to be created are relevant; within the engineering of the product the capabilities and boundary conditions of the production system need to be reflected, see Fig. 1.2.

Facing these dependencies, the engineering of products and production systems are interlinked and in some way equivalent. To understand this interlinking and equivalence, the term engineering needs to be understood. With respect to this book, the definition given by IEEE seems to be most appropriate. In IEEE (1941) engineering is defined as a process consisting of a sequence of activities that creatively apply scientific principles to design or develop structures, machines, apparatus, or manufacturing processes; all as respects of an intended function, economic and safe operation.

All engineers involved in an engineering project of a technical system, together with its necessary technical, economical, and management resources, shall be seen

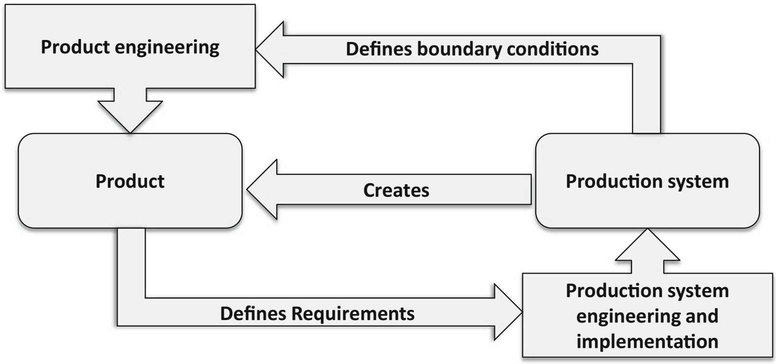

Fig. 1.2 Relations between product and production system based on (Biffl et al. 2016)

as engineering organization. The VDI 3695 Guideline "Plant engineering" (VDI 3695 2009) defines an engineering organization as a set of engineering firms or engineering subunits of a company (supplier, plant manufacturer, plant operator), which is involved in the engineering process of a technical system. This organization is involved in planning, realization, and commissioning of new technical systems and, if necessary, in upgrading, optimizing or modernizing existing technical systems. Note that an engineering organization is the execution environment and the executor of MDE.

Widening the picture of MDE engineering in the field of products and production systems, not only its dependencies buy also its life cycles, shall be reviewed. VDI/VDE (2014a) gives a good overview about these life cycles related to this chapter.

Figure 1.3 provides an overview of activities and their relations to the product and production system life cycle. The product life cycle contains engineering of a product as an individual entity to be sold. However, in this model, engineering of one product is not independent from engineering of the other products to be produced in the considered production system. Here, product line development covers the informed management of similarities and differences of products required to fulfil all relevant costumer needs and (in parallel) to not overburden the technological capabilities of the production system. Finally, a product discontinuation management belongs to each product (product family) as on the one hand customers require information about newer versions of their products to be replaced by new acquisitions and on the other hand technological progress shall be reflected within product lines. To each existing product type, the production system needs to be able to process production orders, which need to be generated, shipped and (possibly) maintained at customer sites.

The link between product and production system is the *production process* executing finally the product creation based on orders. The life cycle of a production system requires engineering of the production system before production execution. In addition, production system engineering requires the development of production

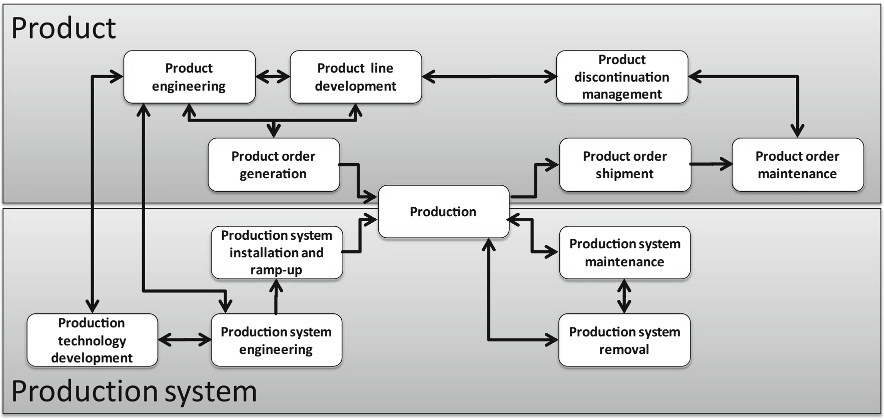

Fig. 1.3 Value-chain-oriented view on the product and production system life cycle based on (VDI/VDE 2014a) and (Biffl and Sabou 2016)

technologies to be applied within the production system. Based on the set of available production technologies (and the set of engineered products), the production system can be engineered and used in production. In addition, the production system life cycle contains production system maintenance activities as well as, in case of production system deterioration, production system removal activities.

Engineering of products and production systems involves several stakeholders. Obviously, these life cycles will add additional stakeholders relevant for the engineering of products and production systems, which especially will be responsible for the definition of the boundary conditions of intended function as well as economic and safe operation of products and production systems as it is intended in the definition of engineering. Figure 1.4 depicts the interactions between the stakeholders.

First, there is the *plant owner*. He is responsible for the economic success of the production system and, therefore, is involved in the definition of the product to be produced and the capabilities of the production system to produce the products.

The plant owner will instruct the *product engineer* with the engineering of the product as described above. He will collect all necessary boundary conditions related to the intended function of the product as well as its economic and safe operation from *potential customers* and *regulation bodies*. In addition, he collects technical boundary conditions related to the necessary production process from the *production system builder*.

In parallel, the plant owner will instruct the *production system builder* (often also named *plant integrator*) to set up a production system able to produce the intended set of products. Together the *production system engineer* and the production system builder will engineer, install, and ramp-up the production system. Therefore, *production system builder* and *engineer* will collect all necessary boundary conditions related to the intended function of the production system from

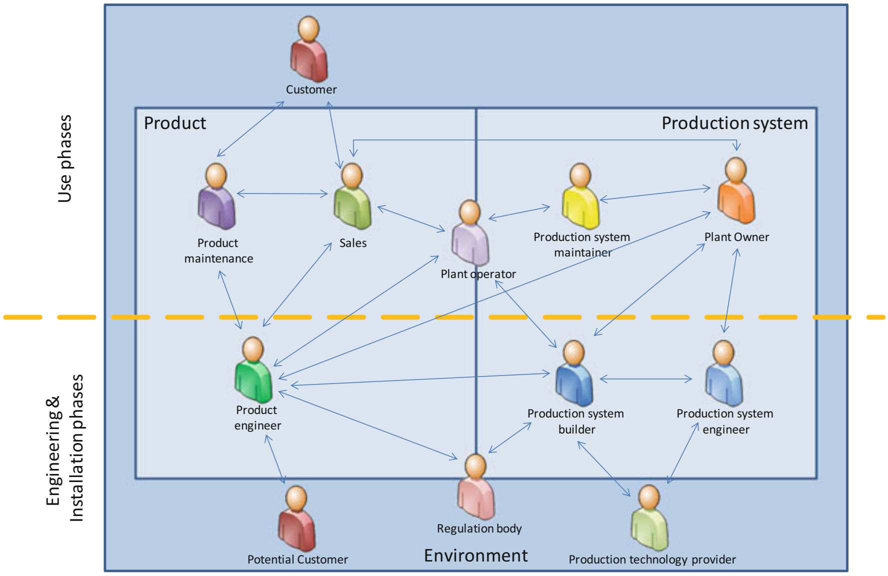

Fig. 1.4 Stakeholders in added-value chains related to industrial plant engineering based on (Biffl et al. 2016)

the *product engineer* and the *production technology provider*. Boundary conditions related to the economic and safe operation of the production system will come from *regulation bodies*, *plant operator*, and *plant owner.*

After the product and production system are engineered and (in case of the production system) set up, the production system can be used by the *plant operator* to produce products. The plant operator will get all necessary information how to produce the product from the *product engineer* and about how to use the production system from the *production system builder*. He will get product orders and their economic and technical boundary conditions, such as the due dates from *sales departments*. To ensure a long-lasting and safe operation of the production system, the *plant operator* interacts with the *production system maintainer*.

After a product has been produced, it is shipped by *sales* to the *customer* to be used. During this use phase of the product, the *customer* may interact with *sales* and *product maintenance* to ensure the economic and safe operation of the product.

Among these stakeholders, information relevant for the engineering of product and production system will be exchanged. The discussion of the complete flow of information goes far beyond the scope of this chapter. Some of the interaction flows will be considered in detail in later chapters of this book. Here, we will focus on discussing selected illustrative examples relevant for product and production system engineering.

- *Potential customers* are a source of information related to boundary conditions for the intended functions of the product to be engineered by the *Product* *engineer*. This information cover for example customer use cases, quality information, product functionality, etc.

- R*egulation bodies* are a source of boundary conditions related to the safe operation of the product to be engineered by the *product engineer*. This includes for example the definition of regulations regarding safety, potential hazards, and environmental issues.
- *Plant owner* and *production system builder* will exchange both requirements to the production system functions and to the production system realization process. Usually, this information includes functional and non-functional requirements within a tender document (in German: *Lastenheft*) and the *plant maker* will reply with a technical specification (in German: *Pflichtenheft*).
- *Production system builder* and *production system engineer* will exchange the same type of information as the *plant owner* and the *production system builder*, but on a more detailed level covering only the parts of the technical system that the *production system engineer* should contribute to.
- Both the *production system builder* and the *production system engineer* will exchange boundary conditions related to the safe operation of the production system with the *regulation bodies*. Examples are pollution regulations, energy consumption monitoring regulations, and human safety regulations.
- In addition, the *production system builder* and the *production system engineer* will exchange information related to possible functions of the production system and its usability in the production and/or production system setup, control, and maintenance. Among others, this covers manufacturing methods, devices required for the realisation of the manufacturing methods, control code used to control the manufacturing methods.

A dependency similar to the dependency between product and production system also exists between production system and production technologies. Within production system engineering and installation, the production system is set up based on the appropriate combination of production system components (Wagner et al. 2010). These components provide capabilities for production process execution (and in addition capabilities for its integration in the production system during installation, ramp-up, and maintenance) and can eventually be regarded as CPPS. These capabilities limit the possibilities within production system engineering and implementation. In the opposite direction, production system engineering requires special production technology capabilities to enable the creation of the intended products, which need to be reflected by production technology development. Thus, the production system in general cause requirements to further production technology development. These dependencies are depicted in Fig. 1.5.

The named dependencies between production systems and production system technologies can also be seen in a different light. Each production system component, which provides certain technological functions used within the production system, is itself a product of a company. These companies act as production technology providers and are interested in fulfilling the needs of their customers, the plant owners and production system builders, to the best extent possible.

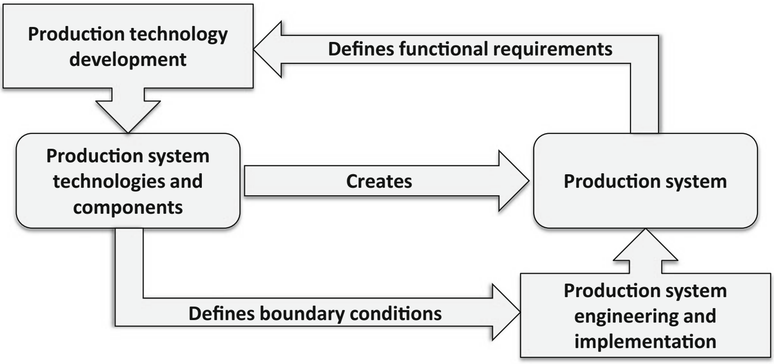

Fig. 1.5 Relations between production systems technologies and the production system based on (Biffl et al. 2016)

The sketched dependencies between product, production system, and production system technologies and components in front of the required efficient engineering involving multiple engineering disciplines is one of the sources of the newly intended comprehensive review and redesign of engineering processes like in the *Industrie 4.0* approach.

Within this initiative, companies and research institutions intend to apply technologies developed within information process and IT sciences for the implementation of flexibility and adaptability capabilities of production system resources and production processes. They are focusing on IoT and CPS (Kagermann et al. 2013). Key elements are (among others)

- Self-aware and self-adaptable production system components,
- The intelligent networking components to provide flexibility on system level using adaptation capabilities and plug-and-work capabilities, and
- The integrated exchange component information related to engineering and runtime phases along the production system life cycle.

As the *Industrie 4.0* component is a controlled part of a production system including manufacturing physics as well as control intelligence the *Industrie 4.0* component shall be considered as a *Cyber Physical Production System* (CPPS) (VDI/VDE 2014b) and shall be considered in the triangle of products, production processes, and resources (production system components). As indicated above, each product requires for its production the processes defined in its product engineering. These processes will be processed on a production system component. Each production system component will process sets of products and will be able to execute processes. Finally, each process is used for the production of products and can be executed by production system components (Pfrommer et al. 2013). Facing this fact, the production process is the lock stone within the roof architecture of the building integrating product, production system, and production system technology and components.

1.3 Research Questions

Looking on the described multi-disciplinary nature of the life cycles of products, production systems, and production system technologies and components, engineers require increasing support to ensure high quality work efficiently. However, this support requires additional research from product engineering, production systems engineering, and informatics communities. Seen from the background of the editors, three of the most interesting research fields related to the necessary support are the field of information modelling, the field of integrated information flows, and the field of key capabilities of the considered objects.

Modelling Within the life cycle of production systems, several information sets are created and applied. It is common sense that these information sets shall be represented by models and other means for description that are best applicable for the involved engineers and technical systems (hard- and software). In this field, the following research questions are of interest.

RQ M1: Modelling the structure and behavior of CPPS. *How can model-based methodologies be exploited to address the specific multi-disciplinary requirements for the representation of the structure and behavior of CPPS?* This question requires for example (a) the consideration of requirements for model-based engineering and model-based application of CPPS, (b) an investigation of usual CPPS architectures, and (c) the exploration of approaches for automating the multi-disciplinary engineering of CPPS.

RQ M2: Modelling in CPPS life cycle phases. *How can model-based methodologies support information creation and processing in the different life cycle phases of a CPPS?* Related to this question are methodologies (a) for the automation of engineering, commissioning, and use of CPPS, (b) for the application of CPPS by service providers or agents, as well as (c) for addressing the quality needs for models of CPPS.

Integrated Information Flows Supporting informed decisions by engineers requires that the relevant information is available when needed in the right quantity and quality independent of its source. This is valid for the life cycles of product, production system, and systems operation. From this need, we derive the following research questions.

RQ I1: Information integration in and across value chains. *Which methods and technologies support the integration on information within and across value chains of products, production systems, and production technologies? Are there benefits accessible from the exploitation of CPPS?* This question addresses for example (a) the links between product, production technology, and production systems engineering, (b) the horizontal and vertical integration within production systems and production value chains, and (c) the digital links between engineering and operation phases.

RQ I2: Quality assurance for information exchange. *Which methods and technologies support assuring the required information quality for information exchange?* This question includes (a) the analysis of typical requirements for the integration of engineering project data coming from heterogeneous data sources and typical requirements in a CPPS supply chain, e.g. concerning the ramp-up of a production system, the examination of multi-disciplinary knowledge integration and representation, as well as (b) the study of required information quality in different life cycle phases of CPPS.

RQ I3: Description of plug-and-play capabilities and interfaces for engineering and run time. *Are there specific aspects of information exchange related to the life cycle of CPPS?* It is assumed that relevant aspects will come from the consideration of typical requirements from product engineering and from production systems engineering on information modelling and integration in the multi-disciplinary engineering of CPPS. For example, the product engineering may provide a description of the production process (required for product creation) in a way enabling its automatic interpretation and execution in the production system. This is only possible with appropriate rich description means.

Key Capabilities of CPPS A CPPS will provide by its nature advanced capabilities like parameterizable function access and provision of state and health information related to necessary activities for its design and use along its life cycle phases, which usually requires cooperative involvement of all technical and informational parts of the CPPS. The support of multi-disciplinary work in this context will benefit from answers on the following questions.

RQ C1: Modelling of CPPS flexibility and self-adaptation capabilities. *How can model-based approaches improve the flexibility and self-adaptation of production systems? What are the roles of product, production technology, and production system models in this context?* This question includes (a) the consideration of typical requirements for flexibility and adaptability in software and in hardware systems, and (b) the analysis of methods and tools for closing the gap between product engineering and production system engineering as well as (c) the analysis of typical requirements for self-adaptation of CPPS.

RQ C2: Linking discipline-specific engineering views for flexible and self-adaptable CPPS. *How shall several disciplines in product and production system engineering be linked to support the engineering of flexible and self-adaptable CPPS?* Within this research question, the exchange of information between both engineering processes and their relation to the problem of cyber physical systems is relevant. Especially the digital shadow of products and production systems need to be considered (Table 1.1).

Table 1.1 Requirements and book chapter contributions: book chapter A addresses research question B strongly (X)

Book chapter A addressing RQ B		M1	M2	I1	I2	I3	C1	C2
Part I	**Product and Systems Design**							
Chap. 2	Product and Systems Engineering/CA* Tool Chains	X	X	X				
Chap. 3	Cyber-Physical Product-Service Systems		X		X			X
Chap. 4	Product Lifecycle Management Challenges of CPPS		X	X			X	X
Part II	**Production System Engineering**							
Chap. 5	Fundamentals of Artifact Reuse in CPPS	X	X					
Chap. 6	Identification of Artifacts in Life Cycle Phases of CPPS	X	X	X	X			
Chap. 7	Description Means for Information Artifacts Throughout the Life Cycle of CPPS	X		X	X			
Chap. 8	Engineering of Next Generation Cyber-Physical Automation System Architectures					X	X	
Chap. 9	Engineering Workflow and Software Tool Chains of Automated Production Systems			X	X	X		
Chap. 10	The Problem of Standardized Information Exchange within Production System Engineering			X	X			
Part III	**Information Modeling and Integration**							
Chap. 11	Model-Driven Systems Engineering: Principles and Application in the CPPS Domain	X	X	X	X			
Chap. 12	Semantic Web Technologies for Data Integration in Multi-Disciplinary Engineering		X	X	X			
Chap. 13	Patterns for Self-Adaptation in Cyber Physical Systems						X	
Chap. 14	Service Oriented Architecture Middleware for Vertical Integration in Industrial Enterprises			X				
Chap. 15	A Deterministic Product Ramp-Up Process—How to Integrate a Multi-Disciplinary Knowledge Base		X	X		X	X	
Chap. 16	Towards Model Quality Assurance for Multi-Disciplinary Engineering—Needs, Challenges, and Solution Concept in an AutomationML Context		X		X			

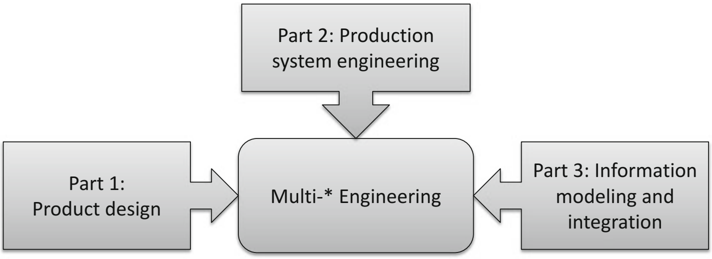

Fig. 1.6 General book structure

1.4 Book Structure

The aim of this book is to provide insight into the field of multi-* engineering, where * can stand for discipline, domain, and/or model. The book is written within the context of the upcoming next generation of production systems envisioned by research and development initiatives, such as *Industrie 4.0* in Germany, *Industrial Internet Consortium* in USA, *Factory of the Future* in France and UK, or *Made in China 2025* from China and will cover the engineering of industrial products and industrial production systems, with their dependencies named above.

The book in hand discusses topics including

- The multi-disciplinary and multi-model nature of engineering processes,
- Data integration needs along the various value adding chains,
- Dependencies between products, production processes, and production systems within engineering processes,
- Architectures of products and production systems enabling improved engineering processes, and
- Needs and approaches for information modelling and integration.

Therefore, the book is structured into three main parts, see Fig. 1.6, dedicated to product design, production system engineering, and information modelling and integration.

1.4.1 Part I: Product Design

Part I on *Product Design* discusses challenges of and approaches for designing and developing products with varying degrees of flexibility. These products provide added value to users and added complexity to production process and system engineers. An important part of engineering is the multi-disciplinary process creating information models for the evaluation of product concepts and for reuse in production systems engineering.

Chapter 2: Product and Systems Engineering/CA Tool Chains* discusses the specifics of engineering processes and the development of CPS from a mechanical engineering design point of view. Emphasis is put on *Model-Based Systems Engineering* (MBSE) methods and the required *software* tools to cope with existing challenges of different domains especially related to system analysis and system integration. The chapter contains a description of data and information flows from an organizational point of view as well as from the product development point of view. This includes information models (e.g., in SysML) as well as organization and tailoring of tools and tool chains.

Chapter 3: Cyber-Physical Product Service Systems is discussing the important topic of product related services, which are deeply integrated in the product development and use like the provision of a machining capability service useable by a producing company. It gives a definition of service-based product service systems (PSS) and unveils the state-of-the-art of CPS-based PSS with major research issues. The evolution from products to solutions and servitization is shown as well as the elements and life cycle of CPS-based PSS including hardware, software, and service elements with integration of product and service life cycles. Based on industrial use cases, this chapter also deals with challenges for engineering a CPS-based PSS in terms of complexity, end user involvement with distributed stakeholders, and involvement of multiple disciplines (e.g., mechanical engineering, information systems, and service science). This discussion of challenges leads to implications for designing engineering processes, particularly cross-domain requirements engineering and design, but also for designing servitized business models enabled by CPS (i.e., business models related to product services).

Chapter 4: Product Lifecycle Management Challenges of CPPS summarizes data and information management issues arising from the advanced use of *Model-Based Systems Engineering* (MBSE) methods that result from engineering processes of smart systems and individualized products with high complexity and variability. The chapter focuses on challenges of the life-cycle integration of products and the respective CPPS especially addressing the information exchange oriented possible dependencies between engineering, production, and use phases of products. Furthermore, data and information management problems coming from integration of the named life cycle phases of products and systems in terms of forward and backward information flows are addressed.

1.4.2 Part II: Production System Engineering

Part II on *Production System Engineering* discusses the design of flexible production systems, which can be adapted effectively and efficiently to provide a scope of production processes and address the challenges coming from products and production processes, which have advanced requirements on flexibility. Key topics are concepts, methods, and tools to deal with dependencies between production system model parts and discipline-specific sub models. An important part is the simulation and virtual commissioning of flexible production systems to reduce the risks coming from added flexibility.

Chapters 5, 6, and 7 build a common frame for the consideration of hierarchical and modular production system architectures and related information along their life cycle. These chapters provide a discussion of the question, which parts of a production system can be regarded as components within the hierarchy and which functionalities and information are assigned to them.

Chapter 5: Fundamentals of Artifact Reuse in CPPS discusses meaningful layers within the hierarchy of production system components and their life cycle. Based on a literature survey and practical experiences candidates for hierarchy layers are identified and their identification criteria are named. In addition, main life cycle phases of production systems are discussed. The thereby developed hierarchy serves as a foundation for the reusability and modularization of *Industrie 4.0* components.

Chapter 6: Identification of Artifacts in Life Cycle Phases of CPPS considers in detail the information sets relevant for a production system component along the life cycle of a production system. For each of the three main life cycle phases named in Chap. 5 relevant artifacts are identified, assigned to the different layers of the production system hierarchy, and discussed against main cases of information reuse within the life cycle of production systems. Thereby, it is intended to enable an identification of hierarchy layers based on relevant information sets.

Chapter 7: Description Means for Information Artifacts Throughout the Life Cycle of CPPS again takes up the artifacts and description means related to them in each of the three life cycle phases on each layer of the hierarchical production system structure as proposed in Chap. 5. These artifacts are clustered and generic artifact classes are derived from the fragmented information artifact landscape. Description means are assigned to the artifact classes, enabling a holisting information management and paving the way for future research on this topic.

Chapter 8: Engineering of Next Generation Cyber-Physical Automation System Architectures provides a summary of non-hierarchical control system architectures that could be applied in industrial automation domain as well as a review of their commonalities. The chapter aims to point out the differences between the traditional centralized and hierarchical architecture to the discussed architectures, which rely on decentralized decision-making and control. The chapter also explores the challenges and impacts that industries and engineers face in the process of adopting decentralized control architectures, analyzing the obstacles for industrial acceptance and the necessary new interdisciplinary engineering skills. In the end, the chapter gives an outlook of possible mitigation and migration activities required to implement decentralized control architectures.

Chapter 9: Engineering Workflow and Software Tool Chains of Automated Production Systems presents an overview of tool chains that are applied in the production system engineering process. The current workflow of production system engineering is described. In particular, three essential phases of the workflow are considered in detail, namely mechanical design, electrical design, and software design. With respect to those essential phases, tool chains are presented that are well established in industry and applied by practitioners. In addition, the tool chain of planning and simulating production processes is discussed. In this regard, various engineering data formats and information that is required as input or results as output by engineering tools is explained. One conclusion that can be derived from the described workflow is the necessity of a standardized data format to exchange engineering data along the entire production system engineering process. As a consequence the role of *AutomationML* as a potential standardized data format is addressed in this chapter and exemplarily presented for the case of virtual commissioning of a production system.

Chapter 10: The Problem of Standardized Information Exchange within Production System Engineering discusses the problem of appropriate structuring (syntax) and meaning (semantics) definition for a file based data exchange technology applicable within information exchange among life cycles, engineering disciplines, and engineering activities of information driven production systems. Based on a set of use cases challenges of the information exchange and application within information driven production systems have been highlighted. The use cases have been accompanied of current standardization activities undertaken to make the use cases possible. In addition, information exchange technologies will be discussed starting with requirements an information exchange technology has to fulfil in an information driven production system and discussing the fulfilment level of these requirements provided by different existing information exchange technologies.

As a special case of file-based information exchange *AutomationML* is considered. It is discussed how *AutomationML* deals with the standardization of syntax and semantics and how the five main challenges of the standardization of data exchange formats can be fulfilled.

1.4.3 Part III: Information Modeling and Integration

Part III on *Information Modeling and Integration* discusses an informatics view on concepts, methods, and software tools for data management in heterogeneous cyber-physical production-system-engineering environments. This part will discuss data models and software solutions exploiting Model-Based System Engineering, Semantic Web, and service-oriented approaches for handling engineering projects of typical size and complexity. Several chapters discuss alternative approaches for representing engineering knowledge as foundation for designing applications to improve the effectiveness and efficiency of engineering processes in the context of multi-disciplinary engineering or CPPS. As a result, the reader can make a better informed decision on which selection of engineering knowledge representation approaches is likely to be most appropriate in a given application context.

Chapter 11: Model-Driven Systems Engineering: Principles and Application in the CPPS Domain discusses advantages and current challenges towards the adoption of model-based approaches in *cyber-physical production system* (CPPS) engineering. In particular, the chapter discusses how modeling languages and model transformations are employed to support current system engineering processes and show their application for a *Pick-and-Place Unit* (PPU) production system.

This chapter follows the model-based software engineering approach, which sees models and their metamodels as the central artifacts for engineering and for automating engineering processes. Abstraction, a key concept of modeling, can become a challenge at integration points during the engineering process in a multi-disciplinary environment, as different stakeholders may choose abstractions that are hard to reconcile with the modeling choices of other stakeholders.

Chapter 12: Semantic Web Technologies for Data Integration in Multi-Disciplinary Engineering investigates how Semantic Web technologies can support multi-disciplinary engineering processes in CPPS engineering. The chapter discusses typical requirements for intelligent data integration and access in the context of CPPS engineering and shows how these can be addressed by Semantic Web technologies and tools. For this, we draw on our own experiences in building Semantic Web solutions for engineering environments as well as on a survey of other Semantic-Web-enabled engineering projects. This chapter summarizes material published in the Springer Book entitled “Semantic Web for Intelligent Engineering Applications” (2016).

This chapter follows the Semantic Web approach, which puts the focus on the representation and integration of linked engineering knowledge as foundation for intelligent engineering applications. The Semantic Web approach originated from the need to harness the heterogeneity of information representation on the Internet. Therefore, the Semantic Web inherently assumes a variety of information models as input to designing software application for automating business and engineering processes.

Chapter 13: Patterns for Self-Adaptation in Cyber-Physical Systems investigates existing studies of CPS with regard to self-adaptation mechanisms and models, applied across the technology stack. From this investigation, we derive recurring patterns and adaptation models, consolidating design knowledge on self-adaptation in CPS, in particular CPPS. The patterns and models can support future CPS designers with the realization and coordination of self-adaptation concerns. Finally, this chapter outlines a research agenda to advance self-adaptation and coordination in the domain of CPS.

Chapter 14: Service-Oriented Architecture Middleware for Vertical Integration in Industrial Enterprises focuses on the technological aspects involved in developing a service-oriented solution for vertical integration in a heterogeneous CPPS context. The chapter addresses the typical state of industrial enterprises and the core technologies currently available for the development of a *gateway service bus* (GSB). Therefore, the chapter will discuss aspects related to enterprise and network architectures, constraints and technologies to discern the challenges to vertical integration and suggest methods for integrating GSBs in enterprises. In addition, the chapter will discuss connectivity strategies and standards that may be used to coordinate the GSB and its services, and to integrate PPS to finally generate a holistic framework for the secure operation of CPPS-based industrial plants.

This chapter follows the *Service Oriented Architecture* (SOA) approach, which represents systems as service interfaces that allow flexibly designing application systems even if the technologies of the underlying services differ and the run-time availability of services changes.

Chapter 15: Deterministic Product Ramp-Up Processes—How to Integrate a Multi-Disciplinary Knowledge Base describes the involvement of a multi-disciplinary knowledge base in a production environment in order to address the challenge of knowledge distribution across product development, production engineering, and elements of the supply chain. The chapter highlights how production data has to be maintained and prepared for the automated support of ramp-up project planning. Through this improvement of planning quality based on reusing existing production knowledge, ramp-up projects can be improved towards deterministic ramp-up processes. This chapter provides an example application for the Semantic Web approach.

Chapter 16: Towards Model Quality Assurance for Multi-Disciplinary Engineering—Needs, Challenges, and Solution Concept in an AutomationML Context discusses how models and their quality play an important role in *multi-disciplinary engineering* (MDE) projects as inputs to and outputs of engineering processes. MDE projects include various disciplines, such as mechanical, electrical, and software engineering. These disciplines apply generic and domain-specific models in their engineering context. Important challenges include model synchronization (of often-heterogeneous input from various disciplines) and *model quality assurance* (MQA) that is covered insufficiently in current MDE practices. The chapter focuses on the needs and approaches for MQA in isolated disciplines as well as in MDE environments, where engineers from different disciplines have to collaborate. Further, the chapter includes related work on MDE and MQA and presents concepts and an initial evaluation of MQA approaches in the context of selected MDE processes.

1.5 Who Shall Read This Book?

This book will be of interest to several target groups: decision makers, product and production system engineering professionals, researchers, and students within the various fields of production system engineering and information processing related sciences. All of these groups will better understand the challenges and needs of engineering project stakeholders coming from the dependencies between products and production systems with increased variability.

Decision Makers, such as industrial managers, and business professionals are interested in a general point of view on how best to make use of the capabilities that products and production systems provide. These groups will take away from this book an up-to-date view on future production system capabilities, in particular, on the challenges of and approaches for designing and developing products with varying degrees of flexibility. The CPPS vision will bring added value to users and added complexity to production process and system engineers. This added value and complexity have to be harnessed by novel kinds of families of systems, such as Product Service Systems or Product Lifecycle Management systems.

To support structuring decision making in a CPPS context, the book will provide better understanding of the benefits and limitations of applicable methods, architectures, and technologies for selected use cases.

Regarding information modelling and integration, the book will highlight the heterogeneous nature of data needed in multi-disciplinary engineering for decision making and explain data integration needs along the various value adding chains. To address data representation and integration the book will support making better informed decisions on which engineering knowledge representation approaches are likely to be most appropriate in a given application context to provide the knowledge needed for making key decisions.

Beyond information modelling and integration, the book will provide inside in the needs of information generation, processing, and use along the life cycle of products and production systems, enabling decision makers to take more informed decisions related to the management and improvement of engineering and use processes within production system environments.

Finally, the book will give an overview on informatics approaches that provide strong contributions to decision making with intelligent information representation, integration, quality assurance, and access in the context of CPPS engineering, such as Model-Based System Engineering, Semantic Web, and service-oriented approaches for CPPS engineering.

Users of Production Systems will become aware of the challenge of knowledge distribution across product development, production engineering, and elements of the supply chain. They will get an overview on approaches to select and use relevant integrated knowledge with appropriate methods, based on case studies, such as *deterministic product ramp-up*.

Engineering Professionals, including engineers of products and of production systems, will become aware of the major challenges of and approaches for designing and developing products with varying degrees of flexibility. They will better understand the viewpoints of the different engineering disciplines involved in CPPS engineering, as well as the benefits and limitations of applicable methods, architectures, and technologies for selected use cases. A core topic is the need for data integration along the various value adding chains, in particular, needs and approaches for information modelling and integration coming from engineering processes of smart systems and individualized products with high complexity and variability.

Product engineers will get better insight into the capabilities of CPPS, so they can consider these capabilities for designing innovative products. They will come to better understand the multi-disciplinary process of creating information models for the evaluation of product concepts and for reuse in production systems engineering, which is essential to achieve the key benefits of CPPS engineering.

Production systems engineers coming from different disciplines, e.g., mechanical, electrical, and software engineering, will better understand architectures of products and production systems enabling improved engineering processes, which in turn is the foundation for improved creative interaction with product engineers, and for understand flexibility options better. They will appreciate approaches for better forward and backward information flow between engineering and operation phases as a foundation for focused improvement of engineering designs and optimizing systems operations with knowledge coming from engineering models.

Finally, both product engineers and production system engineers will get inside in the needs and challenges of the other set of engineers enabling the improvement of a mutual discussion of upcoming challenges within their interaction as well as enabling the reuse of engineering information on both sides.

Researchers from the fields of product engineering, industrial production systems engineering, and information modeling and integration, will benefit from better awareness on the challenges, needs, and approaches in the multi-disciplinary and multi-model engineering of CPPS.

Product engineering researchers can consider how to use the information around engineering to design better capabilities for product engineering processes. They will be introduced to information sources from production systems engineering, e.g., using the emerging standard *AutomationML*, and from operation, e.g., using the standard *OPC UA*, that can be used for improving the product design process.

Industrial production systems engineering researchers will get a better understanding of the challenges and requirements of multi-disciplinary engineering that will guide them in future research and development activities. They will get ideas on how to use the information available around engineering and operation to design better capabilities for CPPS engineering processes. They will become aware of alternatives to hierarchical control system architectures, their potential challenges and impacts on production systems engineering. They will get a better overview of selected tool chains that are evaluated in the production system engineering process towards virtual commissioning, *AutomationML* for data exchange and engineering knowledge accumulation, and selected mechanisms for the self-adaptation in cyber-physical systems. As a consequence, they will be able to make better informed decisions on which engineering knowledge representation approaches are likely to be most appropriate in a given application context.

IT researchers will be enabled to better understand the application domain of CPPS engineering to provide relevant information management methods as a foundation to address the dependencies between products, production processes, and production systems within engineering processes. They will be supported in making the decision on which engineering knowledge representation approaches are likely to be appropriate in a given application context, based on case studies that allow comparing the contributions of Model-Based System Engineering, Semantic

Web, and service-oriented approaches for CPPS engineering. They will get an overview on key IT capabilities for CPPS engineering, such as modeling languages and model transformations, as well as intelligent data integration and access in a heterogeneous CPPS environment, as a foundation for designing and evaluating informatics contributions to CPPS engineering.

Finally, *students* of various disciplines related to production and information processing systems can use this book as textbook to gain understanding of various architectures for information creation, processing, and use within the interrelated life cycles of products and production system. For example, they will find discussions about the interrelations of life cycles, the description of special life cycles, the description of production system hierarchies, and the description of a methodology for defect identification within engineering data.

Thus, students will especially benefit from the book during their final graduation activities finding detailed representation of the state of the art related to multi-domain model-driven engineering.

Acknowledgment This work was supported by the Christian Doppler Forschungsgesellschaft, the Federal Ministry of Science, Research and Economy, and the National Foundation for Research, Technology and Development in Austria.

References

Biffl, S., Sabou, M.: Introduction. In: Biffl, S., Sabou, M. (eds.) Semantic Web Technologies for Intelligent Engineering Applications. Springer, Berlin (2016)

Biffl, S., Lüder, A., Winkler, D.: Multi-disciplinary engineering for *Industrie 4.0* – semantic challenges and needs. In: Biffl, S., Sabou, M. (eds.) Semantic Web Technologies for Intelligent Engineering Applications. Springer, Berlin (2016)

El Maraghy, H.A.: Changeable and Reconfigurable Manufacturing Systems. Springer, London (2009)

Higgins, P., Le Roy, P., Tierney, L.: Manufacturing Planning and Control – Beyond MRP II. Springer, Berlin (1996)

IEEE: Engineers council for professional development. Science. **94**(2446), 456 (1941)

Kagermann, H., Wahlster, W., Helbig, J. (eds.): Umsetzungsempfehlungen für das Zukunftsprojekt *Industrie 4.0* – Deutschlands Zukunft als Industriestandort sichern. Forschungsunion Wirtschaft und Wissenschaft, Arbeitskreis *Industrie 4.0* (2013)

Pfrommer, J., Schleipen, M., Beyerer, J.: PPRS: production skills and their relation to product, process, and resource. In: 18th IEEE Conference on Emerging Technologies and Factory Automation (ETFA 2013), Cagliary, Italy, Proceedings, pp. 1–4, September 2013

Stark, J.: Product Lifecycle Management – Volume 1: 21st Century Paradigm for Product Realisation. Springer, New York (2015)

VDI Richtlinie 3695: Engineering von Anlagen – Evaluieren und optimieren des Engineerings. Beuth Verlag, Berlin (2009)

VDI/VDE:*Industrie 4.0* – Wertschöpfungsketten. VDI/VDE Gesellschaft Mess- und Automatisierungstechnik. Statusreport (2014a)

VDI/VDE-Gesellschaft Mess- und Automatisierungstechnik (GMA): Fachausschuss "*Industrie 4.0*": *Industrie 4.0* – Gegenstände, Entitäten, Komponenten. Status report. http://www.vdi.de/technik/fachthemen/mess-und-automatisierungstechnik/industrie-40/ (2014b). Last access Feb 2015

Vogel-Heuser, B., Diedrich, C., Broy, M.: Anforderungen an CPS aus Sicht der Automatisierungstechnik. Automatisierungstechnik. **61**(10), 669–676 (2013)

Wagner, T., Haußner, C., Elger, J., Löwen, U., Lüder, A.: Engineering Processes for Decentralized Factory Automation Systems, Factory Automation 22. In-Tech, Austria. http://www.intechopen.com/articles/show/title/engineering-processes-for-decentralized-factory-automation-systems