

# Chapter 1

## Introduction

**Stefan Biffl and Marta Sabou**

**Abstract** This chapter introduces the context and aims of this book. In addition, it provides a detailed description of industrial production systems including their life cycle, stakeholders, and data integration challenges. It also includes an analysis of the types of intelligent engineering applications that are needed to support flexible production in line with the views of current smart manufacturing initiatives, in particular *Industrie 4.0*.

**Keywords** Industrie 4.0 • Industrial production systems • Intelligent engineering applications • Semantic Web technologies

### 1.1 Context and Aims of This Book

Traditional industrial production typically provides a limited variety of products with high volume by making use of mostly fixed production processes and production systems. For example, a car manufacturer traditionally produced large batches of cars with the same configuration following the same process and using the same factory (i.e., production system). To satisfy increasingly diverse customer demands, there is a need to produce a wider variety of products, even with low volume, with sufficiently high quality and at low cost and risk. This is a major change of approach from traditional production because it requires *increased flexibility of the production systems and processes*.

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The move toward more flexible industrial production is present worldwide as reflected by relevant initiatives around the globe. Introduced in Germany, *Industrie 4.0*<sup>1</sup> is a vision for a more advanced production system control architecture and engineering methodology (Bauernhansl et al. 2014). Similar initiatives for modernizing industrial production systems have been set up in many industrial countries such as the *Industrial Internet Consortium* in the USA or the *Factory of the Future* initiative in France and the UK (Ridgway et al. 2013). A modern, flexible industrial production system is characterized by capabilities such as

1. *plug-and-participate of production resources* (i.e., machines, robots used in the production systems), such as a new machine to be easily used in the production process;
2. *self-\* capabilities of production resources*, such as automated adaptation to react to the deterioration of the effectiveness of a tool or product; and
3. *late freeze of product-related production system behavior*, allowing to react flexibly to a changing set of products to be produced (Kagermann et al. 2013).

Achieving such flexible and adaptable production systems requires major changes to the entire life cycle of these systems, which, as described in Sect. 1.2, are part of a complex ecosystem combining diverse stakeholders and their tools. For example, the first step of the life cycle, the process of designing and engineering production systems needs to be faster and to lead to higher quality, more complex plants. To that end, there is a need to streamline the work of a large and diverse set of stakeholders which span diverse engineering disciplines (mechanical, electrical, software), make use of a diverse set of (engineering) tools, and employ terminologies with limited overlap (Schmidt et al. 2014). This requires dealing with heterogeneous and semantically overlapping engineering models (Feldmann et al. 2015). Therefore, a key challenge for realizing flexible production consists in intelligently solving data integration among the various stakeholders involved in the engineering and operation of production systems both across engineering domain boundaries and between different abstraction levels (business, engineering, operation) of the system.

Knowledge-based approaches are particularly suitable to deal with the data heterogeneity aspects of engineering production systems and to enable advanced capabilities of such systems (e.g., handling disturbances, adapting to new business requirements) (Legat et al. 2013). Knowledge-based systems support “(1) the explicit representation of knowledge in a domain of interest and (2) the exploitation of such knowledge through appropriate reasoning mechanisms in order to provide high-level problem solving performance” (Tasso and Arantes e Oliveira 1998). *Semantic Web technologies* (SWT) extend the principles of knowledge-based approaches to Web-scale settings which introduce novel challenges in terms of data size, heterogeneity, and level of distribution (Berners-Lee et al. 2001). In such

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<sup>1</sup>Because the term *Industrie 4.0* is the name of a strategic German initiative, the term will be used in its German form, without translation to English.

setting, SWTs focus on large-scale (i.e., Web-scale) data integration and intelligent, reasoning-based methods to support advanced data analytics.

SWTs enable a wide range of advanced applications (Shadbolt et al. 2006) and they have been successfully employed in various areas, ranging from pharmacology (Gray et al. 2014) to cultural heritage (Hyvönen (2012) and e-business (Hepp 2008). A comparatively slower adoption of SWTs happened in industrial production settings. A potential explanation is that the complexity of the industrial production settings hampers a straightforward adoption of standard SWTs. However, with the advent of the *Industrie 4.0* movement, there is a renewed need and interest in realizing flexible and intelligent engineering solutions, which could be enabled with SWTs.

In this timely context, this book aims to provide answers to the following research question:

How can SWTs be used to create *intelligent engineering applications (IEAs)* that support more flexible production processes as envisioned by *Industrie 4.0*?

More concretely the book aims to answer the following questions:

- Q1: What are semantic challenges and needs in *Industrie 4.0* settings?
- Q2: What are key SWT capabilities suitable for realizing engineering applications?
- Q3: What are typical Semantic Web solutions, methods, and tools available for realizing an IEA?
- Q4: What are example IEAs built using SWTs?
- Q5: What are the strengths, weaknesses, and compatibilities of SWTs with other technologies?

To answer these questions, this book draws on several years of experience in using SWTs for creating flexible automation systems with industry partners as part of the Christian Doppler Laboratory “Software Engineering Integration for Flexible Automation Systems”: (CDL-Flex).<sup>2</sup> This experience provided the basis for identifying those aspects of *Industrie 4.0* that can be improved with SWTs and to show how these technologies need to be adapted to and applied in such *Industrie 4.0* specific settings. Technology-specific chapters reflect the state of the art of relevant SWTs and advise on how these can be applied in multidisciplinary engineering settings characteristics for engineering production systems. A selection of case studies from various engineering domains demonstrates how SWTs can enable the creation of IEAs enabling, for example, defect detection or constraint checking. These case studies represent work of the CDL-Flex Laboratory and other research groups.

We continue with a more detailed description of industrial production systems including their life cycle, stakeholders, and data integration challenges (Sect. 1.2). This is then followed by an analysis of what IEAs are needed to support flexible

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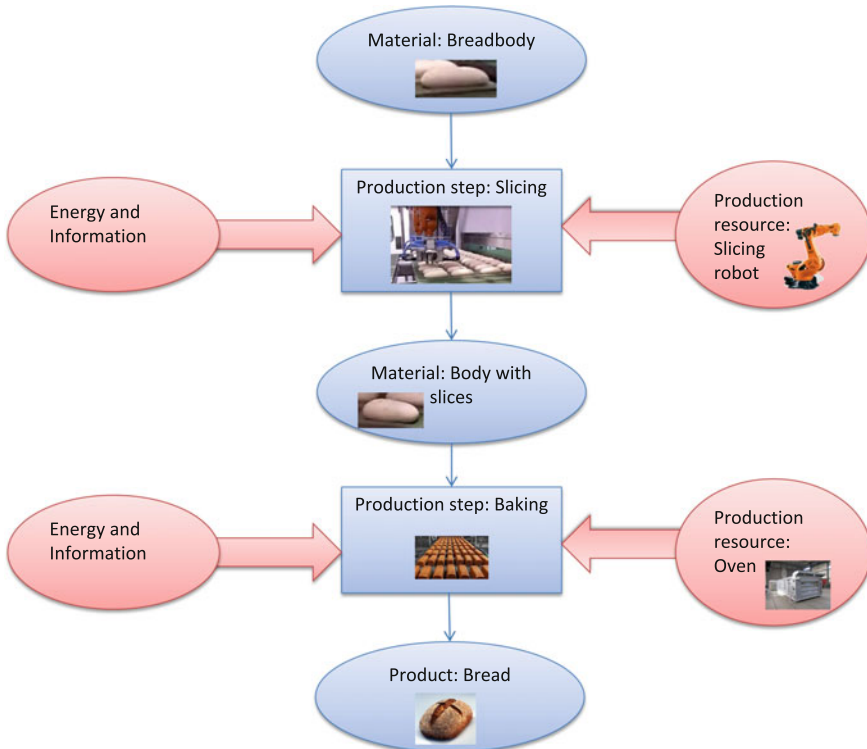
<sup>2</sup>CDL-Flex: <http://cdl.ifs.tuwien.ac.at/>.

production in line with *Industrie 4.0* views (Sect. 1.3). We conclude with a readership recommendation and an overview on the content of this book in Sects. 1.4 and 1.5, respectively.

## 1.2 Industrial Production Systems

Industrial production systems produce specific kinds of *products*, such as automobile parts or bread, at high quality, low cost, and sufficiently fast (Kagermann et al. 2013). The design of the product to be produced in a production system (e.g., a factory, a manufacturing plant) defines the *production process*, i.e., the steps of production (e.g., gluing smaller parts together or drilling holes into a part), with their inputs and outputs (e.g., the raw input parts and the glued or drilled output part).

Figure 1.1 shows a small part of a production process for making bread. The process starts with a semifinished product, the *bread body*, which is input to the first



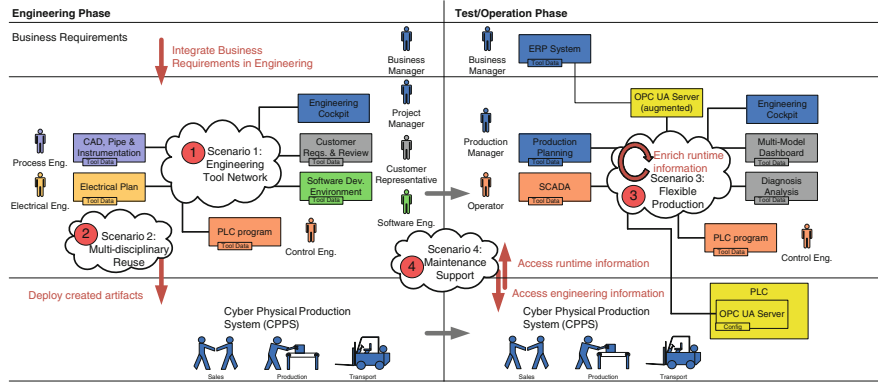
**Fig. 1.1** Part of the production process for making bread

production step of slicing the top of the bread body. The output of this production step, *bread body with slices*, is the input to the next production step, baking the bread, which results in the final product, the *bread*, ready for packaging and delivery to customers. In an industrial production process context, each production step is supported with *production resources*, such as a robot with capabilities for slicing and an industrial oven for baking. The production process and resource need energy and they need to be controlled by programs based on information coming from sensors and human machine interfaces.

In general, the production process can be represented as a network consisting of several input parts and production steps that provide refined outputs and, in the end, the final product. The production steps require *production resources*, such as machines, that have the necessary *capabilities* to conduct the production activity, such as gluing or drilling, including support capabilities, e.g., handling the work piece during production (Tolio 2010).

Production resource capabilities can be provided by humans or machines. Figure 2.9 in Chap. 2 shows the example of a lab-size production system. Chapter 2 provides a more detailed view on industrial production systems and the engineering process of these production systems.

Figure 1.2 illustrates the engineering and operation of an industrial production system (Dorst 2015). There is an important distinction to be made between the two key phases in the life cycle of a production system. First, *the engineering phase* (left-hand side) concerns the planning and design of the production system. The engineering process starts on the top left-hand side with the business manager providing the business requirements to the engineers. During the engineering process representatives from several engineering disciplines, the customer, and project management need to design and evaluate a variety of engineering artifacts. Engineering artifacts include, but are not limited to: (1) the mechanical setup and function of the product and production system; (2) the electrical wiring of all



**Fig. 1.2** Life cycle of industrial production systems: stakeholders, processes and Industrie 4.0-specific scenarios that enable increased production flexibility

devices used in the production system, such as sensors, motors, or actuators, and (3) the software to control the activities of all devices and to orchestrate the contributions of all devices into the overall desired production process. The safety of the production process is an important consideration during the design and evaluation of a production system. The production system design is the input to the construction and deployment of the system in the test and operation phase.

Second, *the test/operation phase* (right-hand side of Fig. 1.2) concerns the running production system, which can be tested, commissioned for production, and will eventually be monitored, maintained, and changed. A business manager uses an *enterprise resource planning* (ERP) system to schedule customer orders for production, based on a forecast of the available production capabilities in the system. On the production system level, the production manager and operator use manufacturing execution systems (MES) for production planning and control; and *supervisory control and data acquisition* (SCADA) systems to orchestrate the independent devices, which have to work together to conduct meaningful and safe production activities. Additionally to planning, other important functions in the test/operation phase are: diagnosis, maintenance, and reorganizing the production system. For example, OPC UA<sup>3</sup> servers provide data from the field level for integration with production planning to support the diagnosis of the current state of the production system.

Figure 1.2 also illustrates important *levels* over an industrial production system as well as the various stakeholders involved in these levels. These levels include (from top to bottom):

- *Business level*: the business manager determines the business requirements, e.g., which products shall be produced at what level of volume, which production process capabilities will be needed;
- *Engineering level*: the project manager, customer representative, and domain experts conduct the engineering process, in which experts from several domains work together to design the production system. During their work, engineers create diverse information artifacts that capture the design of the production system from diverse viewpoints, e.g., mechanical construction drawings, selection of devices, electrical wiring diagrams, and software code and configurations to control the devices and the processes in the overall system;
- *Deployment level*: consists of the deployment of the created artifacts to construct the production system.

As described above, the life cycle of a production system is a complex ecosystem, which combines diverse stakeholders and their tools. Despite their diversity, these stakeholders need to work together to successfully build and operate a production system. To increase the flexibility of the production system and production processes, a better data integration is needed both *horizontally* (among engineering disciplines) and *vertically* (among different levels). These data

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<sup>3</sup>OPC UA: <https://opcfoundation.org/about/opc-technologies/opc-ua/>.

integration processes lay the foundation for IEAs both during the engineering and the test/operation of industrial production systems, as we describe next.

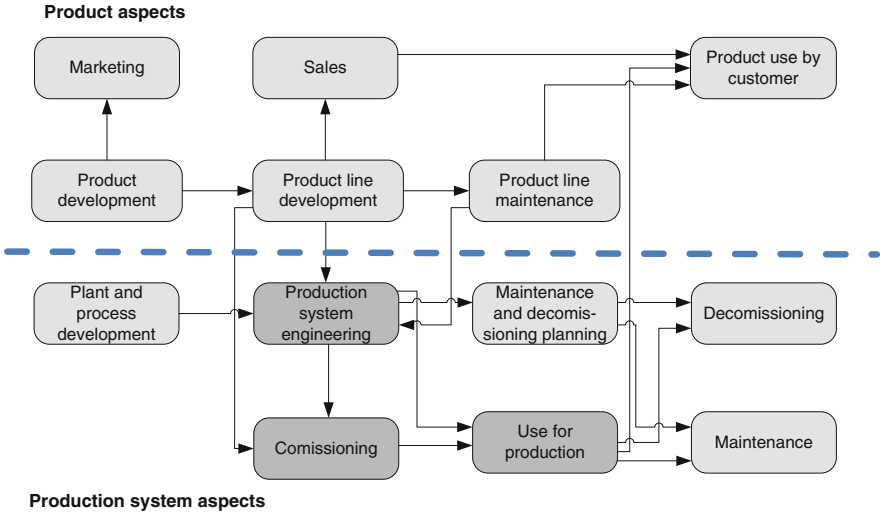
- *Horizontal data integration* includes the data exchange between different engineering disciplines, e.g., mechanical, electrical, and software engineering, which use different terminologies, methods, and tools. Such data exchange is challenging because typical engineering applications are software tools for a specific domain, which know only little about the production system engineering process as a whole or other engineering domains. There is a need for *IEAs* that can build on data integrated over several domains, e.g., to allow searching for similar objects in the plans of several engineering domains, even if terminologies differ.
- *Vertical data integration* also covers the data exchange between systems used to manage the different levels of a production system: business systems, engineering systems, and systems deployed in the field. Traditionally, the data formats on these levels differ significantly and make it hard to communicate changes between the business and field levels leading to applications that are limited to using the data on a specific level. There is a need for *IEAs* that can build on data integrated over several levels, e.g., for fast replanning of the production system operation in case of disturbances in the production system or changes in the set of product orders from customers.

These life cycle views provide the context to consider the contributions of engineering applications and how these can benefit from SWTs.

### 1.3 Intelligent Engineering Applications for Industrie 4.0

The *Industrie 4.0* vision addresses the question of how to provide sufficient flexibility at reasonable cost by representing the major process steps for the life cycle of a product and the life cycle of a production system, which allows producing the product, such as bread or automobiles, as input for the analysis of dependencies between product and production system. The upper half of Fig. 1.3 presents the relevant *life cycle phases of the product* while the lower half depicts the *life cycle phases for the production system* to be considered (VDI/VDE 2014a). The arrows crossing the line between the upper and lower halves provide a focus for the integrated consideration of product and production systems engineering (see also Fig. 2.1).

In Fig. 1.3, the *product life cycle* considers the engineering of products, such as a variety of bread types and automobile types, to be produced in a production system based on customer orders and the development and maintenance of the product lines containing the products. These product lines will impact the required capabilities of the production system. Based on possible products, marketing and sales will force product order acquisition.



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

The *life cycle of production systems* covers the main phases: *Plant and process development*, *Production system engineering*, *Commissioning*, *Use for production*, *Maintenance and decomposition planning*, *Maintenance*, and *Decommissioning*. In these phases, information related to products, production system components, and orders are required and processed leading to a network of information processing entities including humans using engineering tools and automated information processing within machines.

In summary, the current considerations in *Industrie 4.0* require that *information processing has to be enhanced toward a semantically integrated approach*, which allows data analysis on data coming both from product and production system lifecycle processes. In production system engineering, the current focus on data processing has to be moved on to information processing of semantically enriched data.

The vision of *Industrie 4.0* is much broader than creating flexible production systems, as described above. In fact, *Industrie 4.0* envisions the meaningful integration of life cycles relevant for production systems. These life cycles include the important step of engineering (i.e., designing and creating) industrial production systems. The main starting point of *Industrie 4.0* is the integrated consideration of production system life cycles (VDI/VDE 2014a), which include the engineering of industrial production systems.

In this context, *an engineering application is a software tool or a set of software tools for supporting engineering activities*, e.g., for product design and evaluation, e.g., of an automobile or production system part. An *intelligent engineering application* provides functionalities that seem intelligent, e.g., complex analytics for

the optimization of product or production process properties, which are hard to automate. IEAs are a foundation to enable effectively and efficiently key engineering capabilities in industrial production systems, including plug-and-participate of production resources, such as a new machine to be used in the production process (Kagermann et al. 2013).

Figure 1.3 shows that IEAs can depend on information from a wide variety of sources in the engineering process, such as

- the bill of materials, e.g., for describing the materials needed for production,
- the production floor topology, e.g., the layout of production resources,
- the mechanical structure of a set of machines, e.g., robots in a manufacturing cell,
- the wiring plan, e.g., information cables between production resources and control computers, and
- the behavior plan, e.g., software controlling production process of a machine or the orchestration of a complex production process with many steps and sources of disturbances.

Unfortunately, there are many heterogeneous data models used in these information sources, for example, geometric and kinematic models, wiring plans, behavior specifications, and software programs in various representations. The *variety of data sources* is a major challenge that may prevent the sufficiently effective and efficient data exchange between engineering applications and their users.

To enable the engineering and production processes for flexible production systems, integrated information processing intends to ensure the lossless exchange and correct (meaningful) application of engineering and run-time information of a production system to gain additional value and/or to avoid current limitations of production system engineering and use.

In Fig. 1.2, the production system engineering process starts on the top left-hand side with providing the business requirements to the engineers. During the engineering process representatives and tools from several engineering disciplines, the customer, and project management need to design and evaluate a variety of engineering artifacts. These activities run in parallel and may include loops, which may lead to a complex flow of artifact versions in the network of tools used by the project participants. The semantics of engineering data have to be clarified in such a tool network to enable the systematic definition of processes that can be automated to support the domain experts in achieving their goals. SWTs have been shown to be a very good match for addressing the aspects of heterogeneity in data processing for a variety of fields due to their capability to integrate data intelligently and flexibly on a large scale (Shadbolt et al. 2006).

In Chap. 2, we discuss four scenarios (see the red numbered circles in Fig. 1.2) to illustrate the needs for Semantic Web capabilities in industrial production systems engineering and operation.

The first scenario, “*Discipline-crossing Engineering Tool Networks*,” explains in details the goals, challenges, and needs for Semantic Web capabilities in the context of the engineering phase of a single engineering project. This scenario considers the capability to interact appropriately within an engineering network covering different engineering disciplines, engineers, and engineering tools. The scenario further highlights the need for a common vocabulary over all engineering disciplines involved in an engineering organization creating a production system to enable fault free information propagation and use.

The second scenario, “*Use of existing Artifacts for Plant Engineering*,” has a focus on knowledge reuse (and protection) within engineering organizations. This scenario considers the problem of identification and preparation of reusable production system components within or at the end of an engineering project and the selection of such components within engineering activities. Here, the focus is on the required evaluation of component models to decide about the usability of the component within a production system. IEAs can help to analyze candidate components for reuse to support the engineer in evaluating reuse benefits and risks of a large number of candidate components.

The third scenario, “*Flexible Production System Organization*,” details the problem of run-time flexibility of production systems. Here, requirements following the intention of integration of advanced knowledge about the production system and the product within the production system control at production system runtime are sketched. Traditional production systems are fixed and hard to extend, e.g., for including new equipment for monitoring. For a flexible production system, an information system is needed to flexibly integrate production run-time data with engineering knowledge. This facilitates the automation of production planning on the business level, e.g., planning of feasible order volume in a given period, and production scheduling level, e.g., production resource availability and status of production jobs.

The fourth scenario, “*Maintenance and Replacement Engineering*,” describes situations where engineering and run-time information of a production system are combined toward improved maintenance capabilities of production system components. In traditional production systems engineering, the outcomes of the plant engineering process are printed documents on paper or as PDF files, not the engineering models created during the engineering phase. This practice may be insufficient for a flexible production system, if the stakeholders during operation need to reconfigure the production system, e.g., add components with new capabilities. A key question is how to provide engineering knowledge from the engineering phase on the left-hand side in Fig. 1.2 to the operation phase on the right-hand side in Fig. 1.2: what kind of engineering knowledge, made explicit in engineering models, will be needed, and what data exchange format is likely to be most useful?

From these scenarios, the authors of Chap. 2 derive four groups of needs for engineering data integration capabilities:

- engineering knowledge/data representation, integration, and analytics;
- efficient access to semi-structured data in the organization and on the Web;
- flexible and intelligent engineering applications and process knowledge support;
- provision of integrated engineering knowledge at production system run time.

The current approaches for modeling engineering knowledge have shortcomings that SWTs can help overcome. For example, major semantic challenges come from the need to provide tool support for processes that build on heterogeneous terms, concepts, and models used by the stakeholders in production system engineering and operation. Also, most of the knowledge is only implicitly given within the engineering and run-time artifacts of a production system, and has to be modeled and made explicit for further (re-)use. Improved support for the modeling of the semantics of engineering artifacts is required. Chapters 2 and 3 will introduce SWTs and their suitability to address important needs coming from engineering processes, which should be supported with advanced IEAs.

## 1.4 Who Should Read This Book and Why?

This book aims to bridge the communities of industrial production on one hand and Semantic Web on the other. Accordingly, stakeholders from both communities should find this book useful in their work.

Engineers and managers from engineering domains will be able to get a better understanding of the benefits and limitations of using SWTs. Moreover, thanks to the overviews of available technologies as well as the provided best practices for using these, engineers will be enabled to select and adopt appropriate SWTs in their own settings more effectively. Researchers and students interested in industrial production-related issues will get an insight into how and to what extent SWTs can address these issues.

Semantic Web researchers will gain a better understanding of the challenges and requirements of the industrial production domain especially in the light of the emerging *Industrie 4.0* requirements. This will support and guide Semantic Web researchers in developing new technologies and solutions for this important application area more effectively and efficiently.

## 1.5 Book Content and Structure

This book is structured in four parts, as follows.

**Part I: Background and Requirements of *Industrie 4.0* for Semantic Web Solutions.** Part I provides the necessary background information for understanding the rest of the book and covers questions Q1 and Q2 (see Sect. 1.1). Concretely, Chap. 2 describes the problem setting of engineering complex industrial production

systems that match the *Industrie 4.0* vision. Chapter 3 introduces SWTs as a solution alternative for addressing the challenges raised by *Industrie 4.0* settings.

**Part II: Semantic Web-Enabled Data Integration in Multidisciplinary Engineering.** A main conclusion from Part I is that the engineering of complex industrial production systems that match the *Industrie 4.0* requirements happens in highly heterogeneous settings and that SWTs are, by their design, well suited for dealing with such heterogeneity through data integration approaches. Therefore, Part II focuses on how SWTs can be used for data integration in heterogeneous, multidisciplinary engineering settings typical in the creation of flexible production systems. Chapter 4 introduces the general data integration framework called the *Engineering Knowledge Base* (EKB), while the subsequent chapters focus on methods and tools for addressing the various aspects in this overall framework, namely: semantic modeling of engineering knowledge by using ontologies and the transformation of engineering knowledge elements into semantic data (Chap. 5); creating mappings between the semantic data derived from different engineering disciplines (Chap. 6); and managing changes in engineering data (Chap. 7). As such, this part covers question Q3.

**Part III: Creating Intelligent Applications for Multidisciplinary Engineering.** While Part II focuses on a set of methods necessary for data integration in multidisciplinary engineering settings, Part III demonstrates how the integrated engineering data can be used to support the creation of IEAs in line with question Q4. Chapter 8 describes the technical implementation of the data integration framework introduced in Chap. 4. The subsequent chapters focus on presenting IEAs that are enabled by and built on top of the integrated engineering data, namely: product ramp-up (Chap. 9) and industrial simulation (Chap. 10).

**Part IV: Related and Emerging Trends in the use of Semantic Web in Engineering.** Part II and Part III focus on a particular use of SWTs for creating IEAs as developed within the *CDL-Flex* research laboratory. Part IV complements these two previous parts with an outlook on the broader spectrum of approaches that make use of SWTs to support engineering settings. Chapter 11 provides an overview of the field and concludes with a synthesis of emerging trends in this area. As such this chapter places the work performed in *CDL-Flex* within the landscape of related research and motivates the rest of the chapters in part IV. These chapters contribute insights into how SWTs were used in the automotive industry (Chap. 12), for configuration management (Chap. 13), and in the domain of automated production systems (Chap. 14), thus providing further answers to question Q4.

Chapter 15 concludes the book with answers to question Q5 and an outlook on future opportunities in applying SWTs for creating IEAs in the setting of flexible industrial production systems.

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