Stefan Biffl · Marta Sabou *Editors*

Semantic Web Technologies for Intelligent Engineering Applications

Springer

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Foreword I

In the 1970s and early 1980s, the Benetton Group experienced extraordinary growth, increasing the sales from 33 billion lire in 1970 to 880 billion lire in 1985 (the latter figure is roughly equivalent to 1.2 billion euro in today's value), an increase of over 2,500 %.[1] There were several reasons for this commercial success, but arguably, a key reason was the introduction of innovative manufacturing processes, which supported flexible, data-driven product customization. In practice, what Benetton pioneered (among other things) was a model, where clothes were produced undyed and were only finalized as late as possible, in response to data coming from retail sales. This approach was supported by a sophisticated (for the time) computing infrastructure for data acquisition and processing, which supported a quasi-real-time approach to manufacturing. It is interesting that in this historical example of industrial success, we have the three key elements, which are today a foundation of the new world of flexible, intelligent manufacturing: innovative manufacturing technologies, which are coupled with intelligent use of data, to enable just-in-time adaptation to market trends.

The term *Industrie 4.0* is increasingly used to refer to the emergence of a fourth industrial revolution, where intelligent, data-driven capabilities are integrated at all stages of a production process to support the key requirements of flexibility and self-awareness. Several technologies are relevant here, for instance the *Internet of Things* and the *Internet of Services*. However, if we abstract beyond the specific mechanisms for interoperability and data acquisition, the crucial enabling mechanism in this vision is the use of data to capture all aspects of a production process and to share them across the various relevant teams and with other systems.

Data sharing requires technologies, which can enable interoperable data modeling. For this reason, *Semantic Web technologies* will play a key role in this emerging new world of cyber-physical systems. Hence, this is a very timely book,

[1]Belussi F. (1989) "Benetton: a case study of corporate strategy for innovation in traditional sectors" in Dodgson M. (ed) Technology Strategies and the Firm: Management and Public Policy Longman, London.

which provides an excellent introduction to the field, focusing in particular on the role of Semantic Web technologies in intelligent engineering applications.

The book does a great job of covering all the essential aspects of the discussion. It analyzes the wider context, in which Semantic Web technologies play a role in intelligent engineering, but at the same time also covers the basics of Semantic Web technologies for those, who may be approaching these issues from an engineering background and wish to get up to speed quickly with these technologies. Crucially, the book also presents a number of case studies, which nicely illustrate how Semantic Web technologies can concretely be applied to real-world scenarios. I also liked very much that, just like an *Industrie 4.0* compliant production process, the book aims for self-awareness. In particular, the authors do an excellent job at avoiding the trap of trying to 'market' Semantic Web technologies and, on the contrary, there is a strong self-reflective element running throughout the book. In this respect, I especially appreciated the concluding chapter, which looks at the strengths and the weaknesses of Semantic Web technologies in the context of engineering applications and the overall level of technological readiness.

In sum, I have no hesitation in recommending this book to readers interested in engineering applications and in understanding the role that Semantic Web technologies can play to support the emergence of truly intelligent, data-driven engineering systems. Indeed, I would argue that this book should also be a mandatory read for the students of Semantic Web systems, given its excellent introduction to Semantic Web technologies and analysis of their strengths and weaknesses. It is not easy to cater for an interdisciplinary audience, but the authors do a great job here in tackling the obvious tension that exists between formal rigor and accessibility of the material.

I commend the authors for their excellent job.

April 2016

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Foreword II

The engineering and operation of cyber-physical production systems—used as a synonym for *Industrie 4.0* in Germany—need an adequate architectural reference model, secure communication within and in between different facilities, more intuitive and aggregated information interfaces to humans as well as intelligent products and production facilities. The architectural reference model in Germany is RAMI (ZVEI 2015) enlarged by, for example, agent-oriented adaptation concepts (Vogel-Heuser et al. 2014) as used in the *MyJoghurt* demonstrator (Plattform Industrie 4.0: Landkarte Industrie 4.0 – Agentenbasierte Vernetzung von Cyber-Physischen Produktionssystemen (CPPS) 2015). In the vision of *Industrie 4.0*, intelligent production units adapt to new unforeseen products automatically not only with changing sets of parameters but also by adapting their structure. Prerequisites are distinct descriptions of the product to be produced with its quality criteria including commercial information as well as a unique description of the required production process to produce the product, of the production facilities and their abilities (Vogel-Heuser et al. 2014), i.e., the production process it may perform (all possible options). Different production facilities described by attributes may offer their services to a market place. The best fit and most reliable production unit will be selected through matching the required attributes with the provided ones and subsequently adapts itself to the necessary process. There are certainly many challenges in this vision: a product description is required to describe especially customer-specific, more complex products adequately. Different formalized descriptions of production processes and resources are available, e.g., formalized process description (VDI/VDE 2015) or MES-ML (Witsch and Vogel-Heuser 2012), but structural adaptivity is still an issue.

Given that these attributes characterizing product, process and resource were available in a unique, interpretable, and exchangeable way, Semantic Web technologies could be used to realize this vision.

This coupling of proprietary engineering systems from different disciplines and different phases of the lifecycle is already well known since the Collaborative Research Centre SFB 476 IMPROVE running from year 1997 to year 2006 (Nagl and Marquardt 2008). CAEX has been developed in a transfer project of this collaborative research area at first only targeting at a port to port coupling of proprietary engineering tools during the engineering workflow of process plants. The idea is simple and still working: modeling the hierarchy of the resource (plant) in the different disciplinary views and mapping parts of the different discipline specific models to each other. Behavioral descriptions were added with PLCopen XML and geometric models with Collada, resulting in AutomationML, still under continuous and growing development. The future will show whether and how variability and version management—one of the key challenges in system and software evolution—may be integrated in or related to AutomationML. To specify a production facility is already a challenge, but describing its evolution over decades in comparison with similar production facilities and the library for new projects is even worse (Vogel-Heuser et al.; DFG Priority Programme 1593).

The more or less manual mapping from one *AutomationML* criterion in one discipline to another one in the other discipline should be replaced by coupling the discipline specific local vocabularies (ontologies) to a global (joint) vocabulary.

Ontologies have been in focus for more than one decade now, but are still being evaluated in engineering regarding real-time behavior in engineering frameworks on the one hand and regarding dependability and time behavior during runtime of machines and plants.

Semantic Web technologies can help to couple the models from the multitude of disciplines and persons involved in the engineering process and during operation of *automated production systems* (aPS). APS require the use of a variety of different modeling languages, formalisms, and levels of abstraction—and, hence, a number of disparate, but partially overlapping, models are created during engineering and run time. Therefore, there is a need for tool support, e.g., finding model elements within the models, and for keeping the engineering models consistent.

Different use cases for Semantic Web technologies in engineering and operation of automated production systems are discussed in this book, for example,

- To ensure compatibility between mechatronic modules after a change of modules by means of a Systems Modeling Language (SysML)-based notation together with the Web Ontology Language (OWL).
- To ensure consistency between models along the engineering life cycle of automated production systems: during requirements and test case design, e.g., by means of OWL and SPARQL, or regarding the consistency between models in engineering and evolution during operation (DFG Priority Programme 1593), making a flexible definition and execution of inconsistency rules necessary.
- To identify inconsistencies between interdisciplinary engineering models of automated production system and to support resolving such inconsistencies (Feldmann et al. 2015).
- To cope with different levels of abstraction is another challenge; therefore architectural models may be introduced and used to connect the appropriate levels with each other (Hehenberger et al. 2009).

Unfortunately, the key argument against an ontological approach based on Semantic Web technologies is the effort to develop the vocabularies and the mapping between discipline specific vocabularies as well as the rules to check inconsistencies between different attributes described with ontologies. Some researchers propose rule-based agents that map local ontologies to a global ontology (Rauscher 2015), but the domain-specific rules need to be formulated as a basis beforehand, which is a tremendous effort.

For example for more than 15 years, academia and industry are trying to develop a joint vocabulary for automated production systems being a prerequisite for self-aware service-oriented *Industrie 4.0* systems. This process is now part of the *Industrie 4.0* platform activities, but as often, setting up such vocabularies is, similar to standardization activities, difficult, takes time and—because of evolution in technology and methods—never ends. Often such ambitious and theoretically applicable approaches fail due to underestimated effort, shortage of money to cope with the effort and lack of acceptance, i.e., decreasing support from involved companies or companies needed for a successful solution refusing to participate. There will be long-term support needed and tremendous effort from both industry and academia necessary until Semantic Web technologies will gain their full potential.

To extract this knowledge from existing models and projects is certainly worth trying, but requires examples/models of engineering best practices without too many exceptions fulfilling single customer requirements, e.g., in special purpose machinery.

Regarding automation, the key challenges remains: how to agree on a local vocabulary and on domain-specific rules in close cooperation from academia and industry.

January 2016

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Preface

This book is the result of 6 years of work in the Christian Doppler Laboratory "Software Engineering Integration for Flexible Automation Systems" (CDL-Flex) at the Institute of Software Technology and Interactive Systems, Vienna University of Technology.

The overall goal of the CDL-Flex has been to investigate challenges from and solution approaches for semantic gaps in the multidisciplinary engineering of industrial production systems. In the CDL-Flex, researchers and software developers have been working with practitioners from industry to identify relevant problems and to evaluate solution prototypes.

A major outcome of the research was that the multidisciplinary engineering community can benefit from solution approaches developed in the Semantic Web community. However, we also found that there is only limited awareness of the problems and contributions between these communities. This lack of awareness also hinders cooperation across these communities.

Therefore, we planned this book to bridge the gap between the scientific communities of multidisciplinary engineering and the Semantic Web with examples that should be relevant and understandable for members from both communities. To our best knowledge, this is the first book to cover the topic of using Semantic Web technologies for creating intelligent engineering applications. This topic has gained importance, thanks to several initiatives for modernizing industrial production systems, including *Industrie 4.0*[2] in Germany, the *Industrial Internet Consortium* in the USA or the *Factory of the Future* initiative in France and the UK. These initiatives need stronger semantic integration of the methods and tools across several engineering disciplines to reach the goal of automating automation.

We want to thank the researchers, the developers, the industry partners, and the supporters, who contributed to the fruitful research in the CDL-Flex, as a foundation for providing this book.

[2]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.

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Vienna, Austria
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Stefan Biffl
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Abbreviations

3D	3 Dimensional
AAA	Anyone is Allowed to Say Anything About Any Topic
AML	AutomationML, Automation Markup Language
API	Application Programming Interface
AS	Automation Systems
ASB	Automation Service Bus
ASE	Automation Systems Engineering
ATL	Atlas Transformation Language
AutomationML	Automation Markup Language
BFO	Basic Formal Ontology
BOM	Bill of Material
CA	Customer Attribute
CAD	Computer-Aided Design
CAEX	Computer-Aided Engineering Exchange
CC	Common Concepts
CE	Conformité Européene, European Conformity
CIM	Computer Integrated Manufacturing
CPK	Process Capability Index
CPPS	Cyber-Physical Production System
CSV	Comma Separated Values
CWA	Closed World Assumption
DB	DataBase
DE	Domain Expert
DIN	Deutsches Institut für Normung e.V.
DL	Description Logics
DP	Design Parameter
ECAD	Electrical CAD, Electrical Computer-Aided Design
EDB	Engineering Data Base
EDOAL	Expressive and Declarative Ontology Alignment Language
EKB	Engineering Knowledge Base

EMF	Eclipse Modeling Framework
EngSB	Engineering Service Bus
EO	Engineering Organization, Engineering Object
ERP	Enterprise Resource Planning
ETL	Extraction, Transformation and Load
FB	Feed Backward control
FF	Feed Forward control
F-Logic	Frame Logic
FLORA-2	F-Logic translator
FOAF	Friend-of-a-Friend
FPY	First Pass Yield
FR	Functional Requirement
HDM	Hyper-graph Data Model
HTML	Hypertext Markup Language
HTTP	Hypertext Transfer Protocol
I/O	Input/Output
I4.0	Industrie 4.0
IC	Integrated Circuit
ICT	Information and Communication Technologies
IDEF	Integrated Definition Methods
IEA	Intelligent Engineering Application
IRI	International Resource Identifier
JSON	JavaScript Object Notation
JSON-LD	JSON for Linking Data
KCMA	Knowledge Change Management and Analysis
KE	Knowledge Engineer
LD	Linked Data
LED	Linked Enterprise Data
LOD	Linked Open Data
MBE	Model-Based Engineering
MBSE	Model-Based Software Engineering
MCAD	Mechanical CAD, Mechanical Computer-Aided Design
MDE	Model-Driven Engineering
MDEng	Multidisciplinary Engineering
MDWE	Model-Driven Web Engineering
MES	Manufacturing Execution System
MM	MetaModel
MOF	Meta Object Facility
MOFM2T	MOF Model To Text Transformation Language
nUNA	Non-Unique Name Assumption
OBDA	Ontology-Based Data Access
OBII	Ontology-Based Information Integration
ODP	Ontology Design Pattern
OKBC	Open Knowledge Base Connectivity
OMG	Object Management Group

OPC UA	OPC Unified Architecture
OWA	Open World Assumption
OWL	Web Ontology Language
OWL DL	Web Ontology Language—Description Logic
OWL2	Web Ontology Language 2
OWL-S	OWL Services
P&ID	Piping and Instrumentation Diagram
PDF	Portable Document Format
PLC	Programmable Logic Controller
PM	Project Manager
ppm	parts per million
PPR	Product–Process–Resource
PPU	Pick and Place Unit
PROV-O	Provenance Ontology
PV	Process Variable
QFD	Quality Function Deployment
QVT	Query/View/Transformation
QVTo	QVT Operational
R2R	Run to Run control
RCS	Relational Constraint Solver
RDB	Relational Database
RDF	Resource Description Framework
RDF(S)	RDF Schema
RDFa	Resource Description Framework in attributes
RML	RDF Mapping Language
RM-ODP	Reference Model of Open Distributed Processing
ROI	Return on Investment
RQ	Research Question
RUP	Rational Unified Process
SCADA	Supervisory control and data acquisition
SDD	Specification-Driven Design
SE	Software Engineering
SEKT	Semantic Knowledge Technologies
SHACL	Shapes Constraint Language
SHOE	Simple HTML Ontology Extensions
SKOS	Simple Knowledge Organization System
SPARQL	SPARQL Protocol and RDF Query Language
SPC	Statistical process control
SPIN	SPARQL Inferencing Notation
SQL	Structured Query Language
SUMO	Suggested Upper Merged Ontology
SW	Semantic Web
SWRL	Semantic Web Rule Language
SWT	Semantic Web technologies
SysML	Systems Modeling Language

TCP	Transmission Control Protocol
TGG	Triple Graph Grammar
UC	Use Case
UML	Unified Modeling Language
UNA	Unique Name Assumption
URI	Uniform Resource Identifier
URL	Uniform Resource Locator
VCDM	Virtual Common Data Model
VDE	Verband der Elektrotechnik Elektronik Informationstechnik e.V. (Association for Electrical, Electronic & Information Technologies)
VDI	Verband Deutscher Ingenieure (Association of German Engineers)
W3C	World Wide Web Consortium
WG	Working Group
WWW	World Wide Web
XML	Extensible Markup Language
XSD	XML Schema Definition

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*[1] 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

[1]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).[2] 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

[2]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

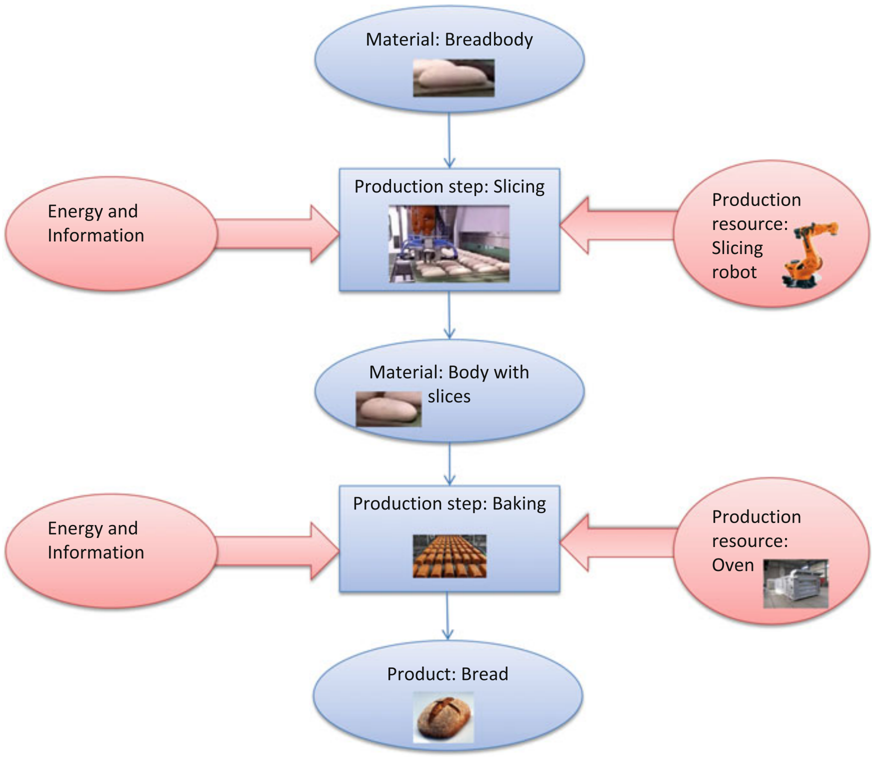

Fig. 1.1 Part of the production process for making bread

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

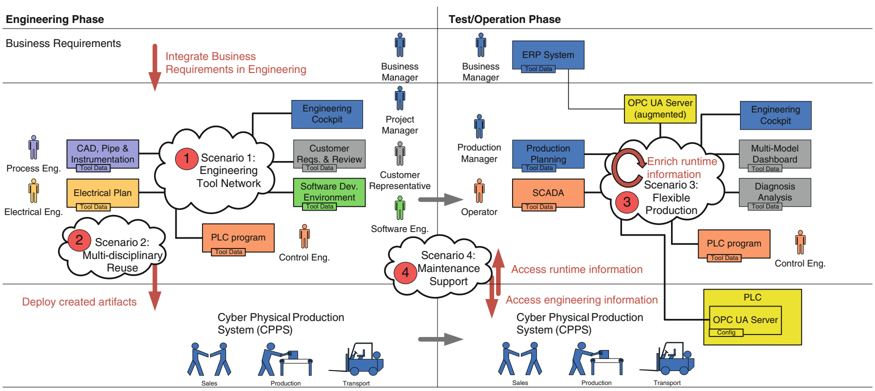

Fig. 1.2 Life cycle of industrial production systems: stakeholders, processes and Industrie 4.0-specific scenarios that enable increased production flexibility

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[3] 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

[3]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.

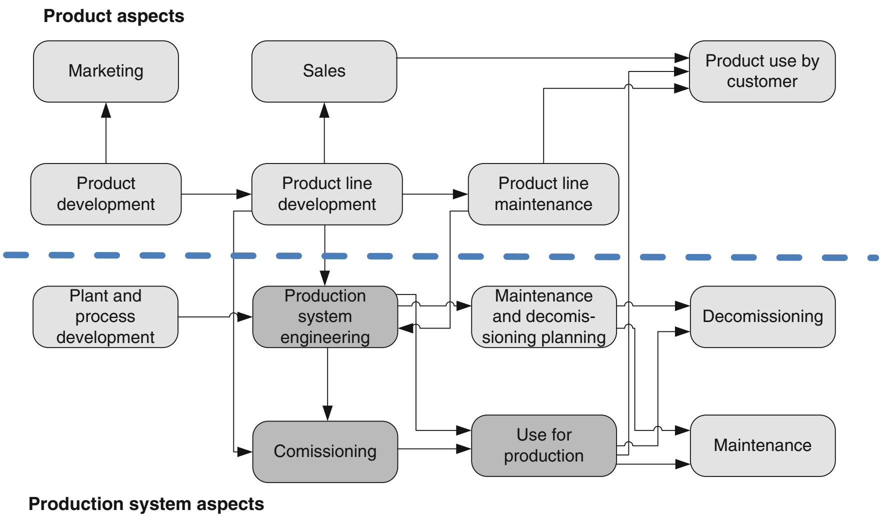

Fig. 1.3 Value-chain-oriented view on the product and production system life cycle based on (VDI/VDE 2014a)

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: