STUTTGARTER BEITRÄGE ZUR PRODUKTIONSFORSCHUNG

URSULA MARIA RAUSCHECKER

Method to Configure Agile Production Networks for Personalised Products Based on Customisable Manufacturing Services

Universität Stuttgart

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Method to Configure Agile Production Networks for Personalised Products Based on Customisable Manufacturing Services

Von der Fakultät Konstruktions-, Produktions- und Fahrzeugtechnik der Universität Stuttgart zur Erlangung der Würde eines Doktor-Ingenieurs (Dr.-Ing.) genehmigte Abhandlung

Vorgelegt von
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Vorwort

Die vorliegende Arbeit entstand im Rahmen meiner Tätigkeit als wissenschaftliche Mitarbeiterin, Projektleiterin und Gruppenleiterin am Fraunhofer-Institut für Produktionstechnik und Automatisierung IPA in Stuttgart.

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Stuttgart, im Mai 2019 Ursula Rauschecker

Short Summary

To remain competitive, manufacturing enterprises need to address current trends such as the increasing demand for individualised products, as well as rising product complexity. Together with outsourcing business and production processes, which do not form part of an enterprise's core business, this becomes a major challenge when it comes to managing production networks. Agile production networks, which are established for specific orders by flexibly combining manufacturing services, can contribute towards overcoming this issue in the future.

Therefore, this thesis proposes an IT-based method for connecting customisable manufacturing services that aims at efficiently configuring agile production networks while reducing the necessary know-how at the same time.

First, this includes, the provision of manufacturing services by manufacturers publishing service descriptions on a common platform. These services can then be selected, configured, and connected to establish agile production networks. While configuring the networks, potential dependencies between the combined manufacturing services and their properties must be considered. To support this, the developed system provides recommendations derived from previously-defined connections between manufacturing services.

The developed method, model, and IT system have been evaluated by means of an application in the organic semiconductor industry. As a result, it has been confirmed that the developed solution contributes to the reduction of efforts and know-how involved in the participation in agile production networks for manufacturing service providers and consumers, thus lowering the barriers for exploiting benefits of agile production networks such as increase in sales or utilisation of external competencies and resources. Furthermore, the solution turned out to be beneficial especially for configuring complex products, if utilising flexible automated manufacturing systems, and if numerous pre-defined configurations are available in the knowledge base.

Kurzinhalt

Um ihre Wettbewerbsfähigkeit zu gewährleisten, müssen produzierende Unternehmen aktuellen Entwicklungen wie der zunehmenden Nachfrage nach kundenindividuellen Produkten und einer steigenden Produktkomplexität begegnen. In Kombination mit der Auslagerung von Prozessen, die nicht dem Kerngeschäft der Unternehmen entsprechen, stellt dies eine Herausforderung für das Management von Produktionsnetzwerken dar. Agile Produktionsnetzwerke, die basierend auf Fertigungsdiensten auftragsspezifisch zusammengestellt werden, tragen dazu bei, diese in Zukunft bewältigen zu können.

Aus diesem Grund befasst sich diese Arbeit mit der Bereitstellung einer IT-gestützten Methode zur Verknüpfung konfigurierbarer Fertigungsdienste mit dem Ziel, eine effiziente Zusammenstellung agiler Produktionsnetzwerke zu ermöglichen und gleichzeitig das dafür benötigte Fachwissen zu verringern.

Dafür werden Beschreibungen von Fertigungsdiensten zunächst von den anbietenden produzierenden Unternehmen in einer Plattform hinterlegt. Von dort aus stehen sie für die Auswahl, Konfiguration und Einbindung in agile Produktionsnetzwerke zur Verfügung. Während der Konfiguration dieser Netzwerke sind mögliche Abhängigkeiten zwischen den kombinierten Fertigungsdiensten und ihren Eigenschaften zu berücksichtigen. Um dies zu erleichtern, stellt das entwickelte System Empfehlungen bereit, die aus im Vorfeld konfigurierten Verknüpfungen zwischen Fertigungsdiensten abgeleitet werden.

Das entwickelte Verfahren wurde anhand eines Anwendungsbeispiels aus der organischen Halbleiterindustrie erprobt. Dabei bestätigte sich, dass die entwickelte Lösung zur Verringerung der für die Konfiguration agiler Produktionsnetzwerke notwendigen Aufwände und Fachkenntnisse beiträgt und damit sowohl für produzierende Unternehmen als auch für die Konsumenten personalisierter Produkte die Hürden für die Ausschöpfung der Potentiale agiler Produktionsnetzwerke senkt. Darüber hinaus wurde die Eignung des Verfahrens insbesondere beim Einsatz flexibler automatisierter Fertigungssysteme und einer großen Wissensbasis, sowie für die Zusammenstellung von Produktionsnetzwerken bzw. Produkten mit hoher Komplexität festgestellt.

Contents

Abbreviations and Symbols

Abbreviations

AI	Artificial Intelligence
AP	Application Protocol
B2MML	Business To Manufacturing Markup Language
BOM	Bill of Materials
BPMN	Business Process Modelling Notation
BRIC	Brazil, Russia, India, and China
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CDD	Common Data Dictionary
CPA	Classification of Products by Activity
CPC	Central Product Classification
DIKW	Data, Information, Knowledge, Wisdom
DXF	Drawing Interchange Format
EDI	Electronic Data Interchange
ERP	Enterprise Resource Planning
ESB	Enterprise Service Bus
eOTD	Electronic Commerce Code Management Association (ECCMA) Open Technical Dictionary
GDP	Gross Domestic Product
GPC	Global Product Classification
GUI	Graphical User Interface
HMI	Human Machine Interface
IGES	Initial Graphics Exchange Specification
ISIC	International Standard Industrial Classification
IT	Information Technology
JAX-RS	Java API for RESTful Web Services
JSON	JavaScript Object Notation
JT	Jupiter Tessellation
KPI	Key Performance Indicator
MaaS	Manufacturing-as-a-Service

MES	Manufacturing Execution System
NACE	Statistical Classification of Economic Activities in the European Community (Nomenclature statistique des activités économiques dans la Communauté européenne)
NAICS	North American Industry Classification System
OLED	Organic Light-Emitting Diode
OPC UA	Open Platform Communications Unified Architecture
OPV	Organic Photovoltaic
OWL	Web Ontology Language
PLC	Programmable Logic Controller
PPS	Production Planning and Control System
PRR	Production Rule Representation
QoS	Quality of Service
RDF	Resource Description Framework
RNTD	RosettaNet Technical Dictionary
RTD	Real-Time Data
RuleML	Rule Markup Language
SaaS	Software-as-a-Service
SCADA	Supervisory Control and Data Acquisition
SCM	Supply Chain Management
SCOR	Supply Chain Operations Reference
SEMI	Semiconductor Equipment and Materials International
SiLA	Standardisation in Lab Automation
SLA	Service Level Agreement
SME	Small or Medium-sized Enterprise
SoA	Service oriented Architecture
SPARQL	SPARQL Protocol and RDF Query Language
SSL	Secure Sockets Layer
STEP	Standard for The Exchange of Product model data
SWRL	Semantic Web Rule Language
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
UBL	Universal Business Language
UDDI	Universal Description, Discovery and Integration
UML	Unified Modelling Language
UN/EDIFACT	United Nations Electronic Data Interchange For Administration, Commerce and Transport
UNSD	United Nations Statistical Division
USDL	Unified Service Description Language
USP	Unique Selling Proposition
WMS	Warehouse Management System

WS-BPEL	Web Services Business Process Execution Language
WSDL	Web Services Description Language
WSLA	Web Service Level Agreement
X3D	Extensible 3D
XML	Extensible Markup Language
XPDL	XML Process Definition Language
XSD	XML Schema Definition
XSLT	Extensible Stylesheet Language Transformations
YAWL	Yet Another Workflow Language

Symbols

A	Amount of dependency endpoints (e.g. categories)
A_{oled}	Area of an OLED element
C	Set of all manufacturing service categories
c_i	Category of manufacturing service i; $c_i \in C$
D	Set of all dependencies between manufacturing service instances
d	Dependency; $d \in D$
i, j, x, y, z	Variables, e.g. manufacturing service placeholders and related indices
I, J, X, Y, Z	Set of manufacturing services i, j, x, y, z
k, l, t, u	Indices; $k, l, t, u \in \mathbb{N}; k, l, t, u \geq 1$
λ	Failure rate
m	Amount of levels in a category tree
$M(d)$	Multiplicity of elements d in D
mi_i	Manufacturing service instance of manufacturing service i
n	Number of iterations to increase set of assessment results
P_{oled}	Power consumption of an OLED element
P_y	Set of all parameters of a manufacturing service y
p	Parameter, manufacturing service characteristic
pc	Parameter category
pi	Parameter instance
pr	Parameter restriction
V_x	Set of parameter values of manufacturing Service x
pv	Parameter value
$R_{description}(x, y)$	Expression indicating that x has a relation to y which is of type *description*
s	Share of matching parameters in a total set of a manufacturing service's parameters
w	Weighting factor

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1. Introduction

Manufacturing is a major pillar of European economy as its share of value creation and employment is approximately 20%, which is higher than that of any other industry, trade, and service sector (European Commission 2014, p. 127). However, the competitiveness of manufacturing businesses in the high-wage countries of Europe or the US is no longer guaranteed by technology leadership and optimised efficiency. Brazil, Russia, India, and China (BRIC) and other low-wage countries are rapidly catching up on knowledge and the adoption of technology, as well as purchasing power (Santana, Aparecida do Nascimento Rebelatto et al. 2014, Malerba and Nelson 2011). As a result, manufacturing shares in Gross Domestic Products (GDPs) have been continuously decreasing in high-wage countries over the recent years (Westkämper 2014, p. 9). To overcome this and remain competitive, manufacturing companies from high-wage countries are not focusing on cost leadership only anymore, but also on pushing towards differentiation by concentrating on their core business, i.e. skill and capital-intensive activities (Kinkel 2012), to establish and sustain Unique Selling Propositions (USPs).

Besides technology and innovation leadership, differentiation in manufacturing is, according to Lanza, Moser et al. (2012) and Volberda, Morgan et al. (2011, p. 179–180), driven by addressing specific customer needs and trends, e.g. by implementing individualisation, regionalisation, sustainability, services, or niche market strategies. In this context, customisation is recognised as one of the most promising strategies to maintain the competitiveness of the European manufacturing industry (Westkämper 2014, p. 15, European Commission 2013, pp. 92–96). It is already considered throughout many industry sectors, such as computer, automotive, garment, or furniture industries, where mass customisation strategies are widely implemented (Salvador, de Holan et al. 2009, Kodzi and Gazo 2010). Even more, manufacturing trends are even pointing towards personalised production, i.e. the manufacturing of products which is not restricted by predefined variants, but by the range of options made available by flexible manufacturing systems (Mourtzis and Doukas 2014b). Interactive value creation, customer co-design, or crowd sourcing in manufacturing are concepts which further develop this trend by involving customers and their needs to the product design process (Reichwald and Piller 2009, p. 235). Up to now, total customisation concepts are only applied for high-value products such as in the aerospace or medical industries, or simple but potentially high-value added consumer products such as garments (Koren 2010, pp. 80–87).

1.1. Motivation and Problem Statement

Personalised production applications are currently restricted by the efforts and costs involved in managing and executing personalised production. These strongly depend on the complexity of related products, i.e. the number of product components and processes involved, as well as their interdependencies (Inman and Blumenfeld 2014, Nußbaum 2011, p. 22). Furthermore, customisation has an impact on the whole production network, since customisation options usually are not restricted to finishing processes, but also affect product components and processes delivered by a network of suppliers (Mourtzis and Doukas 2014a, Ost and Mandel 2009). As a result, total customisation is accompanied by the need for agile production networks, i.e. the ability of these networks to adapt to changing requirements (Ramesh and Devadasan 2007). To deal with the challenges of product complexity and production network agility, appropriate enterprise co-operations must be implemented in the form of agile production networks as shown in figure 1.1.

For involved companies, participation in such agile production networks offers the potential to increase market access and satisfy customer preferences, as well as improve capacity utilisation, get access to external competencies, and exploit

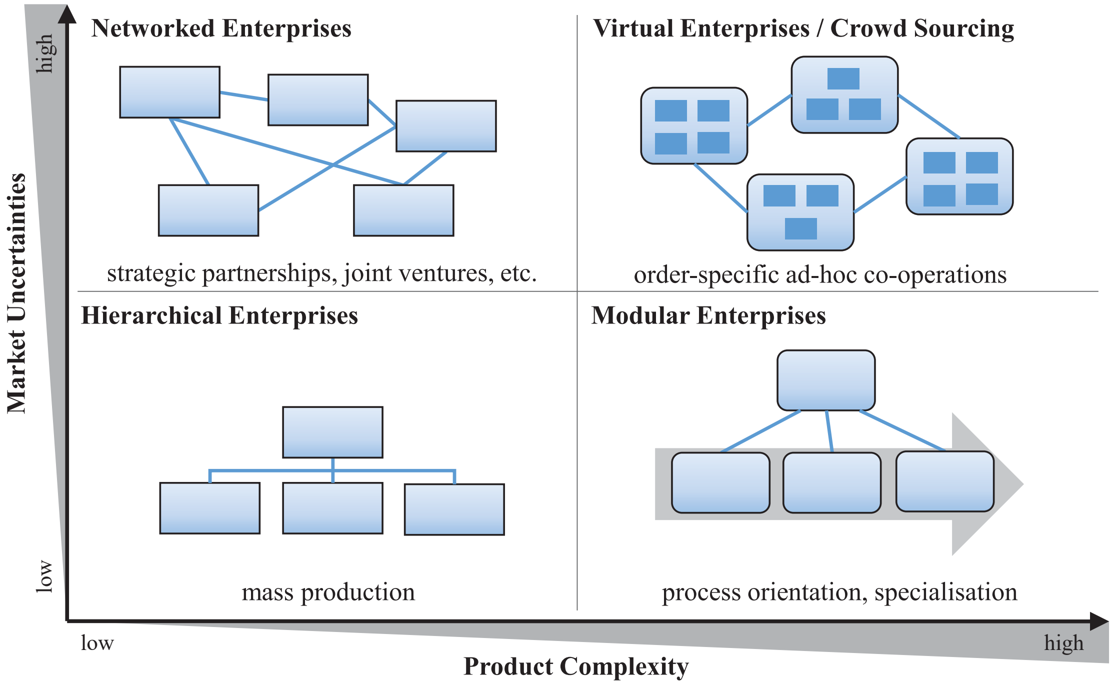

Figure 1.1. Enterprise cooperations as per Reichwald, Möslein et al. (2000, p. 42)

synergies (Markaki, Panopoulos et al. 2013, Romero and Molina 2011, Wong and Lesmono 2011). However, since pre-defined production networks become order-specific as personalised production progresses, the efforts involved in supplier selection and integration, as well as order management, increase respectively. Accordingly, there is no guarantee that potential benefits of participating in agile production networks will remain valid on considering implementation efforts (Schuh and Meyer 2009). To counter this, i.e. to configure agile production networks in an efficient and beneficial way, it is necessary to apply appropriate IT methods and tools that support related tasks (Mourtzis and Doukas 2014a, Grenz and Pfadenhauer 2012, Reichwald and Piller 2009, pp. 37–39).

1.2. Objective and Approach

IT solutions to support the configuration of agile production networks must incorporate efficient and effective methods and tools for sharing, integrating, and connecting manufacturing services, i.e. production capabilities and capacities, including related customisation possibilities (Rauschecker, Stöhr et al. 2013). Therefore, the objective of this thesis is to develop a method, together with an IT system to support it, which simplifies the configuration of agile production networks by aiding the creation of ad-hoc production network structures. A major focus is on the connection of manufacturing services, where appropriate measures ensure the manufacturability of the final individual product. These measures include the verification of the plausibility of the combination of processes, products, and their characteristics. In doing so, total product customisation is enabled by considering the configuration ranges of the manufacturing services integrated.

To achieve this objective, the approach shown in figure 1.2 is applied:

Chapter 2 outlines the scope of this work. It defines major terms and describes the initial situation, i.e. principles and existing infrastructures for production networks for personalised products.

Chapter 3 derives requirements and boundary conditions for the method and related IT system based on the major challenges in typical workflows to freely configure order-specific production networks for personalised products.

Chapter 4 describes the state of the art. The research gap that is dealt with in this work is identified by comparing the requirements specified in chapter 3 with existing solutions. This sets the method and IT system developed apart from previous work.

Chapter 5 gives an overview of the method for creating agile production networks for personalised production by on configuring and combining manufacturing services. It serves as basis for the developments explained in chapters 6 and 7.

Chapter 6 outlines the proposed solution, i.e. data model and IT system, for configuring and combining manufacturing services for personalised production. This includes concepts for the description of manufacturing services, i.e. the underlying capabilities and capacities, the connection of manufacturing services, and the suggestion and verification of these connections.

Chapter 7 explains the implementation of these concepts in detail, i.e. the model components, their realisation and application.

Chapter 8 validates the functionalities and benefits of the method, model, and IT system by means of an industrial application from the organic semiconductor industry and compares the results with the requirements derived in chapter 3.

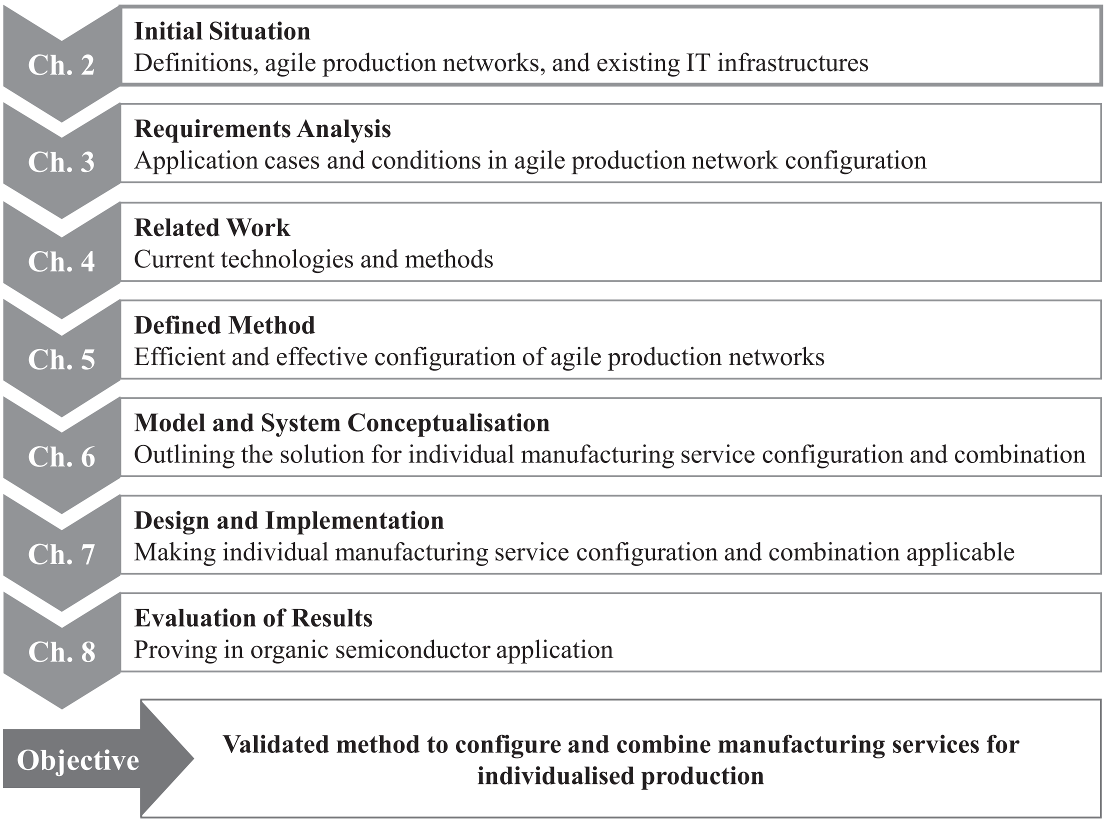

Figure 1.2. Overview of the approach and structure of this work

2. Initial Situation

The following sections describe the application context and conditions relevant to the configuration of agile production networks. In doing so, an emphasis is placed on individualised production, service-based manufacturing, and supportive IT tools.

2.1. Totally Customised Production

About 100 years ago, Henry Ford stated that “Customers can have any colour for their car, as long as it is black”. By introducing assembly lines in mass production, he made manufacturing more efficient and products such as cars affordable for a large number of people (Hopp and Spearman 2011, pp. 24–25). However, the competitiveness of this approach is no longer guaranteed, since the demand for customised products has been growing continuously over the recent years (Piller 2007). Not only the number of industry sectors providing customised products has grown, but also the degree of customisation is increasing continuously. It appears that both trends will continue (Weiss and Schweiggert 2013, Schmitz 2013).

Mass customisation is defined as the ability to meet the needs of almost every customer while retaining the same production efficiency as with mass production (Piller 1998, p. 65). To achieve this, in the past, customisation options have been offered to end-users mainly by modularising products, processes, production facilities, and supply chains in order to implement build-to-order strategies and enable alternative components to be easily replaced (Landherr 2014, pp. 22–25, Mandel 2012, pp. 32–36, Lindemann and Maurer 2006, Salvador, Forza et al. 2002). Such mass customisation principles have been implemented in a wide range of industries, from the clothing and computer sectors to furniture and automotive industries (Azouzi, D'Amours et al. 2010, Ost and Mandel 2009, Fogliatto, da Silveira et al. 2012). However, as related mass customisation infrastructures are based on pre-defined components and variants, they do not allow completely individual specification of products.

By contrast, totally customised or personalised production supports customisation by involving customers in the design process, allowing them to configure, select, and combine modules without restrictions (Koren 2010, pp. 77–79). This picks up on the concepts of one-of-a-kind production introduced by Wortmann (1991), which differentiate customised production by the degree to which activities in the value chain are customer-order driven, and by the type of offer (product-based or capability-based) made to the customer. To enable personalised production, customisation options supplied by a manufacturing resource must be made available based on its capabilities. In other words, for example, totally customised production does not offer to manufacture a product of varying size by selecting from pre-defined values, but rather allows the respective parameters to be freely configured, provided that they are within the range given by the physical restrictions of that manufacturing resource. In doing so, it addresses the demand to increase the degree of customisation as it occurs for high-value and luxury goods (Mourtzis and Doukas 2014b), in medical industry, where it is required to adapt applications to patients' needs (e.g. Hieu, Zlatov et al. 2005), as well as for the application of technologies which are highly customisable by default, such as additive manufacturing and incremental sheet forming (Eyers and Dotchev 2010, Heinzl, Harnisch et al. 2006).

To enable totally customised production, a major pre-condition is the adaptability of respective production systems to each individual customer order. Since products and their components are usually manufactured by means of multiple process steps executed throughout distributed production systems, product personalisation affects the whole production network (Gosling, Naim et al. 2013). To enable and align the production of totally customised products throughout such networks, all their elements must be integrated in order to align product and information exchange across production network participants. Elements to be considered during integration include the manufacturing resources able to execute individually-configured processes, the control thereof, knowledge about manufacturing processes and products to be manufactured by these resources, as well as supply chain management.

The available capabilities and capacities of the manufacturing resources concerned, including parameterisation options for order-specific configurations, need to be shared with potential consumers and other participants in the production network. In doing so, the knowledge about product and process characteristics must be represented in a way that enables comparing the various manufacturing capabilities and capacities. Additionally, to ensure their utilisation within the production network, the capabilities and capacities of manufacturing resources have to be integrated to common business and Supply Chain Management (SCM) processes. To support knowledge representation and SCM process integration, as well as the efficient overall management of agile production networks, respective IT tools integrating manufacturing resources to the production network management need to be established. The combination of these components, i.e. knowledge about manufacturing capabilities, SCM and their IT-based representation and integration, is supplied to agile production networks in the form of manufacturing services. These customisable manufacturing services are individually configured and combined to address individual product specifications.

This is illustrated in figure 2.1, which puts manufacturing resources, supply chain management, and the handling of knowledge in context with the objective to achieve totally customised production throughout agile production networks by identifying manufacturing services as tool to integrate them respectively.

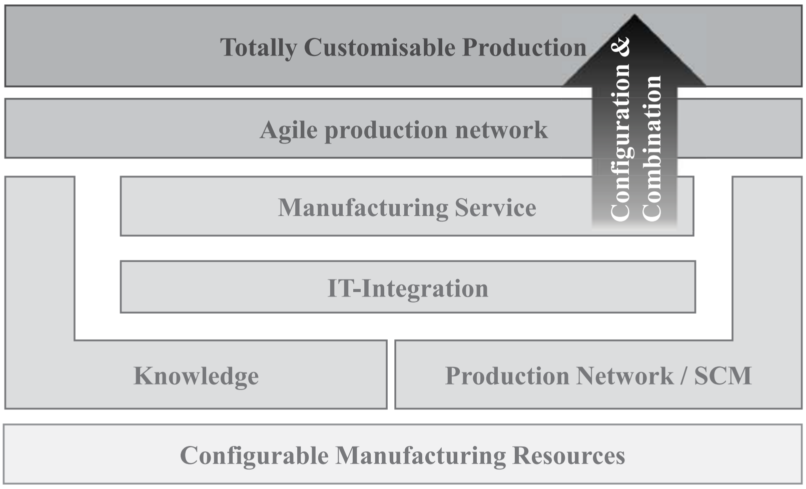

Figure 2.1. Pillars of totally customised production

2.2. Definitions

As indicated in section 2.1, manufacturing services, supply chain management, and knowledge management are major topics to be considered when individually configuring products and the respective production networks. For this reason, this section explains the terms and concepts relevant to these topics and puts them in relation to the configuration of agile production networks.

2.2.1. Manufacturing Services

Among others, a service is defined as “the particular skills that someone has and can offer to others” (Walter 2008). Transferred to the production domain, this means that it is the process of creating a product that is sold by manufacturers rather than the pre-defined final product itself. In practice, this is usually implemented by means of contract manufacturing, which requires considerable management effort to establish strategic partnerships and set-up of framework contracts (Akbarzadeh and Pasek 2008). As a result, related production network structures are established in the long term. However, personalisation of products requires production network participants to be involved in a more flexible and efficient way.

To address this, concepts from the IT domain are considered, where service orientation is implemented by encapsulating single functionalities, which are integrated to potentially distributed systems via defined interfaces, and which can be shared and orchestrated within Service oriented Architectures (SoAs) to achieve higher-level functionalities (Josuttis 2008, p. 15–30, MacKenzie, Laskey et al. 2006). By applying standardised interfaces, service descriptions, and Service Level Agreements (SLAs), such services can be integrated and executed efficiently and potentially automatically.

When transferring these principles to the manufacturing domain and combining contract manufacturing with SoA principles, personalised products can be manufactured in an efficient, service-based manner. Accordingly, cloud manufacturing, or Manufacturing-as-a-Service (MaaS) concepts have been developed, which are based on the virtual representation of manufacturing resources and their integration and management within SoAs (Xu 2012, Tao, Zhang et al. 2011).

2.2.2. Supply Chain Strategies

For logistics in general, major objectives apply, namely to provide the right *product* at the right *time* at the right *place* in the right *quantity* and the right *quality* at the right *costs* (Krampe and Lucke 2006, p. 20–21). These objectives must also be considered when companies define their value creation strategies and production networks, including the scope of value adding processes and make or buy decisions, as well as the selection of appropriate suppliers considering their capabilities, capacities, location, costs, and market positions (Schönsleben 2011, pp. 70–145).

Supply chains or production networks are designed or managed by means of planning, sourcing, making, and delivery processes as specified in the Supply Chain Operations Reference (SCOR) model shown in figure 2.2. This is usually applied from a single company's perspective, which means that only first tier suppliers and customers are considered, as further interactions would significantly increase complexity and management effort.

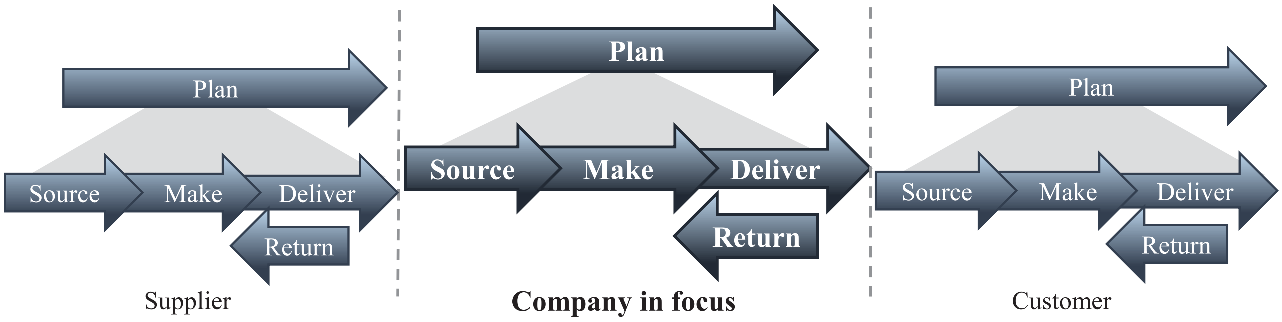

Figure 2.2. SCOR model according to Stephens (2001)

2.2.3. Knowledge and Knowledge Management

To share and interpret information across different organisations, as it is required for the distributed manufacture of personalised products, it is essential to process knowledge. Knowledge about the products to be manufactured and available manufacturing services must be distributed and applied throughout the production network. Various definitions of knowledge in the context of enterprises and IT systems refer to the structure of hierarchical Data, Information, Knowledge, Wisdom (DIKW) as shown in figure 2.3 (cf. Faucher, Everett et al. 2008). *Data* in the form of bits, bytes, and characters, which cannot be interpreted due to the lack of structure and context, form the basis for extracting *information*. This is done by structuring the data, i.e. expressing their relationships by adding syntax to them. In the same way, *knowledge* is generated by adding context to the information, enabling it to be interpreted and inferences to be derived. This serves as basis for *wisdom* which is generated by identifying patterns and trends from the layers below.

Semantic technologies, especially ontologies, can be used to manage and represent this knowledge. According to Hitzler, Krötzsch et al. (2008, p. 12), an ontology is perceived as a knowledge base, i.e. a document which models knowledge about an application domain by means of standardised languages such as Resource Description Framework (RDF) or Web Ontology Language (OWL). Its objective is to make knowledge machine-readable, as well as to synchronise the meanings and relations of terms throughout the application domain (Sicilia 2006). To ex-

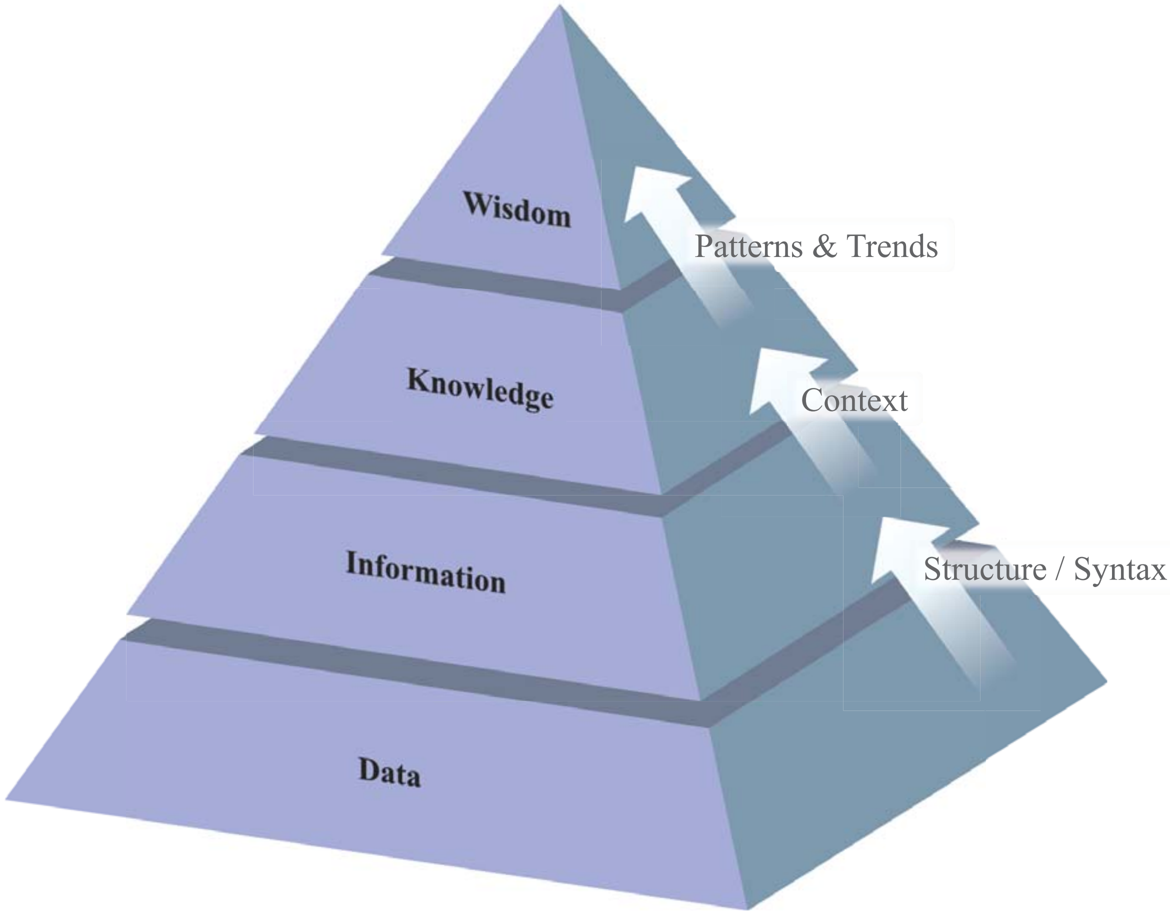

Figure 2.3. Knowledge Pyramid derived from Faucher, Everett et al. (2008)

ploit ontologies, they must be accessed, i.e. analysed by means of requests and inference rules. This can be achieved by using query languages such as SPARQL Protocol and RDF Query Language (SPARQL) (Hitzler, Krötzsch et al. 2008, pp. 202–239).

2.3. Agile Production Networks

When customers specify and order personalised products, these are usually not manufactured by a single factory, but rather by distributed production systems. As mentioned in section 2.1, this requires the flexible integration and combination of manufacturing resources which provide customisation options via manufacturing services. These manufacturing services must be selected from a pool, configured, and connected according to individual product specifications. The result of this, i.e. the combination of configured manufacturing services, is referred in this work as agile production network. The main feature of such agile production networks is their configurability throughout all the related elements of integrated production systems. This includes manufacturing resources executing specific production processes, as well as the arrangement of these resources in specific supply chains.

2.3.1. Configurability of Manufacturing Resources

To manufacture personalised products in agile production networks, the capabilities of manufacturing resources supplied to the network must be configurable to support customised product or process specifications. This can be achieved by implementing different flexibility concepts as they are described by D'Souza and Williams (2000) or Vokurka and O'Leary-Kelly (2000), and summarized in table 2.1.

Flexibility dimension	Definition	Individualisation support
Machine and process	Range of operation/part variants to be processed without changing a facility's setup	Enables individualisation within equipment-specific ranges
Material and handling	Ability to process and handle a variety of materials and parts	Enables individualisation within equipment-specific ranges
Product variety	Ability to adapt manufacturing resources to new product specifications, e.g. by integrating new components	Enables individualisation based on the modularity of the production system, implementation efforts are higher than for equipment configuration

Table 2.1. Production flexibility concepts and their relevance for individualisation

These kinds of configurability in production systems can be realised by modularising manufacturing equipment and parameterising related processes. This also corresponds with the preconditions of production system reconfiguration (Bengel 2010, p. 32) from which it can be derived that to adapt a production system to specific product configurations either the production equipment, process, or task parameters must be changed. In doing so, the extraction and provision of real options available from production systems make the full range of individualisation options offered by the manufacturing system accessible, which would otherwise be restricted by pre-definitions from product engineering (Bengtsson 2001). The range of available customisation options depends on process characteristics and the degree of automation. For highly automated systems, such as those implemented for high volume manufacturing, e.g. in the automotive industry, the configuration options are, if available, generally restricted to pre-defined options. If high degrees of customisation are available, these are invariably implemented based on processes and related machines which have numerous configuration options on their own, as it is the case, for example, for coating, machining, and additive manufacturing processes.

2.3.2. Impact of Personalisation on Production Networks

On production network level, products are individualised mainly by means of mass customisation concepts, primarily assemble-to-order and build-to-order, which are based on product modularisation and pre-defined components and variants (e.g. Mandel 2012, Salvador, Rungtusanatham et al. 2004). To optimise efficiency and lead times, order entry points in these networks are positioned as close to the end-customer as possible (Schönsleben 2011, pp. 371–399). However, this cannot be applied for realising personalised production, since for this, customisation options must go beyond those of typical mass customisation, and order entry points would potentially be located at the start of respective supply chains. This calls for different concepts which focus on flexibility and speed rather than costs (Schuh and Meyer 2009). Figure 2.4 shows the most relevant ones and differentiates them from mass customisation principles.

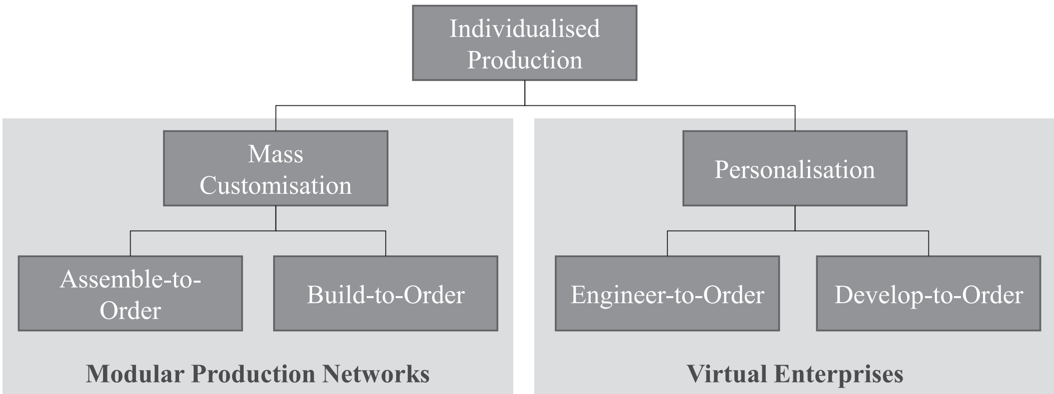

Figure 2.4. Individualisation concepts and related supply chain strategies derived from Schönsleben (2011) and Koren (2010)

For instance, in *engineer-to-order* systems, no inventories are kept for (semi-) finished products, and at least parts of the final products have to be engineered before production is executed (Schönsleben 2011, p. 208). Accordingly, *virtual enterprises* are established as short-term, order-specific cooperations between independent participants from a strategic network, which act towards customers as a single organisation (Schönsleben 2011, p. 116).

2.3.3. Configuration of Ad-Hoc Supply Chains

Due to their high degree of flexibility and customer interaction, supply chain concepts for personalised production require product and production network lifecycles to be closely and immediately aligned, as shown in figure 2.5.

When designing products and associated production networks, two types of flexibility facilitate the adaption to customised specifications: the configurability of manufacturing resources as described in section 2.3.1, and the ability to easily combine or exchange manufacturing resources in the network as outlined in section 2.3.2. For this reason, setting up agile production networks to suit individual product specifications involves significant management and integration efforts. These result from the selection and integration of appropriate contributors with appropriate capabilities, as well as of configuration options to ensure the manufacturability of personalised products. Furthermore, they are also due to the

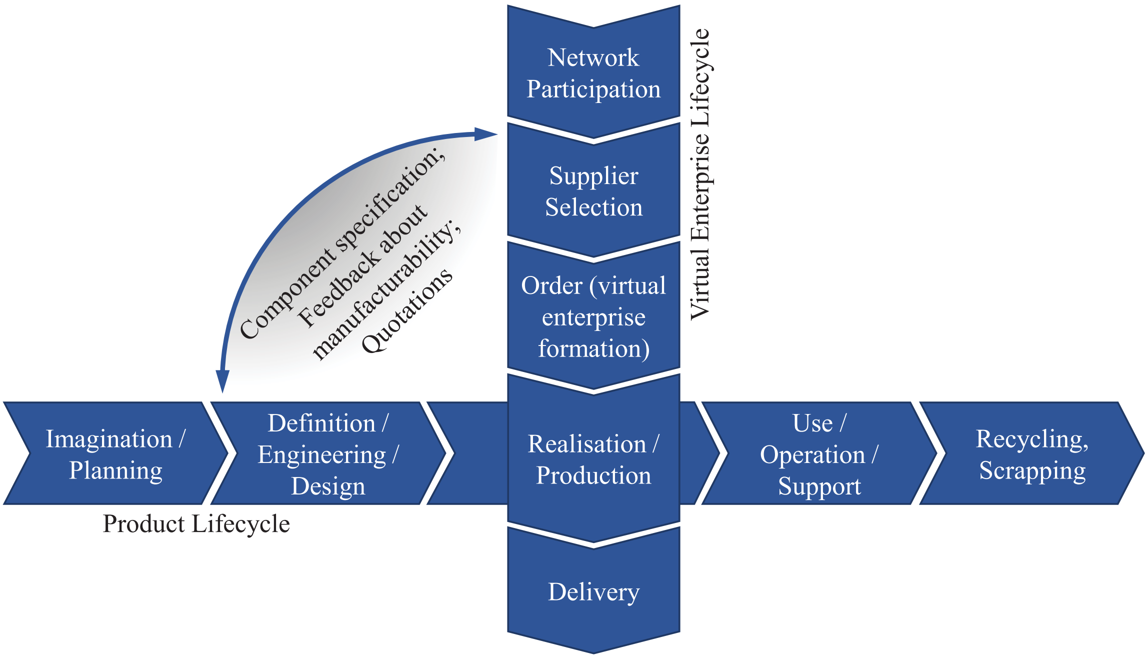

Figure 2.5. Dependencies in product and production network configuration derived from Stark (2015, p. 6–7) and Schönsleben (2011, p. 116–118)

definition of optimum routes through the network, i.e. the selection of alternative manufacturing processes with regard to performance indicators, primarily costs, lead times, and quality (cf. Lanza, Moser et al. 2011, Schönsleben 2011, p. 94–96).

To deal with these configuration tasks, i.e. to reduce management efforts and make agile production networks beneficial, suitable IT tools are essential, since these can support the configuration of agile production networks by aiding decisions concerning the selection of appropriate manufacturing capabilities, as well as the integration with manufacturing resources in order to access up-to-date information and shorten response times (e.g. Gunasekaran, Lai et al. 2008, Afsarmanesh and Camarinha-Matos 2005, Tuma 1998).

2.3.4. Benefits of Agile Production Networks

Besides improving performance by combining virtual enterprises with IT concepts, agile production networks also provide their participants with the potential benefits of enhanced operation and concentrating on core competences. These are achieved by support with selecting optimal suppliers and collaborators, collaborative design, as well as integrated execution and monitoring of product development and operations (Markaki, Panopoulos et al. 2013, Cao and Dowlatshahi 2005). According to Rauschecker, Meier et al. (2011), these benefits are relevant for two groups of participants in agile production networks:

Manufacturers, who are able to strengthen their market position by providing personalised products. They could also benefit from an increased visibility of their capabilities and improved market access via the production network, for instance if they are not able to provide final products on their own, or if related platforms for customer interaction are provided. Especially small enterprises can integrate and exploit complementary manufacturing capabilities and personalisation options via agile production networks. Furthermore, companies can optimise the utilisation of their manufacturing resources by sharing spare capacities.

Customers and product designers, who purchase products or product components from manufacturers can implement new and individual product ideas and designs without access to own manufacturing expertise and facilities.

2.4. IT-Landscape in Practice

Since IT systems are considered as key enablers for configuring agile production networks efficiently and effectively, this section gives an overview of current IT infrastructures and systems for configuring products and related manufacturing systems.

2.4.1. Integration of Manufacturing Resources

IT systems in manufacturing are typically implemented in a hierarchical structure as it is represented by the automation pyramid in figure 2.6. On the *cell or line control* layer, sensors and actuators are integrated to exchange analogue or digital signals such as measurement results or triggers. These are typically processed by Programmable Logic Controllers (PLCs), which run machine control functions executing manufacturing operations on machines. Whole production lines or factories are usually controlled on the *manufacturing operations* layer, where Manufacturing Execution Systems (MES) are implemented to plan production jobs in detail, as well as to execute and track them. Business tasks, such as purchasing and handling customer orders, are implemented by means of Enterprise Resource Planning (ERP) systems on the *business planning and logistics* layer. Various standards are utilised to integrate these layers, such as Open Platform Communications Unified Architecture (OPC UA) and Business To Manufacturing Markup Language (B2MML) (Boyd, Noller et al. 2008, pp. 40–42).

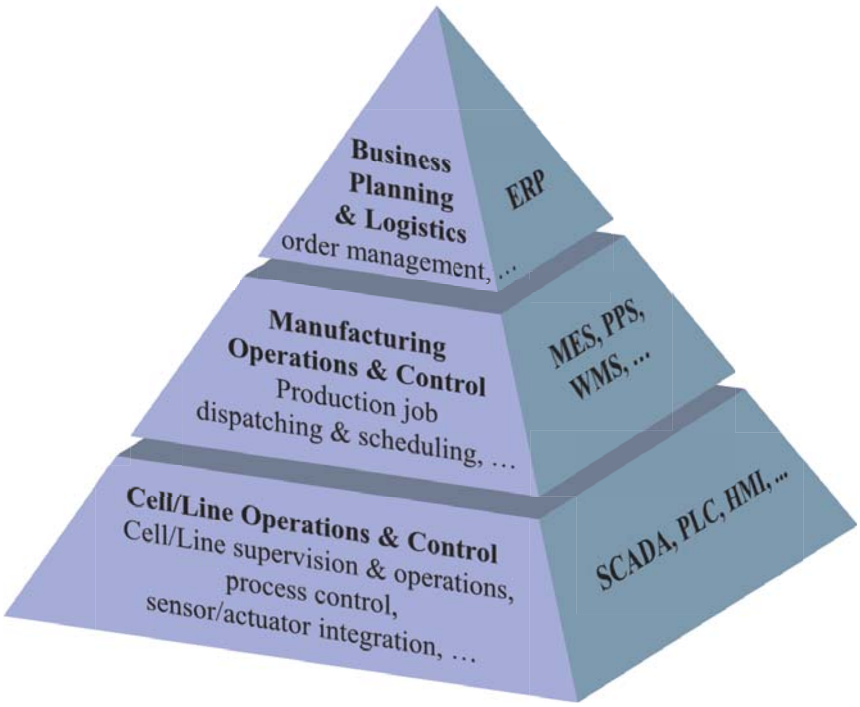

Figure 2.6. Automation pyramid according to IEC 62264-1:2013

2.4.2. IT for Supply Chain Management and Integration

IT tools to support Supply Chain Management usually focus on related processes within a specific enterprise. Functionalities related to production network interaction, particularly order management and purchasing, are usually integrated to the ERP layer (see figure 2.6).

However, especially when it comes to complex products, this is not sufficient to enable seamless and efficient interaction with other production network participants. For this reason, communication between different production sites and companies is often executed by means of Electronic Data Interchange (EDI), which allows business documents, primarily quotations, orders and their confirmations, as well as invoices, to be exchanged in a machine-readable format (Senn 1992). As EDI is rather a concept than a specific standard, various implementations exist, e.g. Universal Business Language (UBL) (Bosak, McGrath et al. 2013), United Nations Electronic Data Interchange For Administration, Commerce and Transport (UN/EDIFACT) and its industry specific subsets, for instance Odette for the automotive sector and EANCOM for consumer goods (Zimmermann 2007). There are also standards such as RosettaNet, which originates from the electronics and semiconductor industry (Witczyński and Pawlak 2005), and myOpenFactory, which is tailored to the needs of machinery and plant engineering (Wienholdt, Schmidt et al. 2007).

Since EDI is restricted to standardised business documents, further solutions must be implemented if the integration of production network participants is also expected to cover more detailed product and production process information, such as specifications. Furthermore, message formats usually vary across enterprises or software systems, which requires appropriate data transformation. Enterprise Service Buses (ESBs) are implemented to address these needs, as they provide integration capabilities for IT services, message routing and transformation, as well as workflow configuration and execution, which can be configured specifically for each integration application (Vernadat 2009).

2.4.3. Product Customisation Support

The direct selection of customisation options by customers without the involvement of human intermediaries is most often enabled by web-based product configurators, which generally visualise the resulting product (Blecker, Friedrich et al. 2005, pp. 80–93). For mass customised products, configuration options are modelled onto product variants and alternative product components, which are managed and combined according to order-specific Bills of Materials (BOMs) by IT systems at ERP level (Steger-Jensen and Svensson 2004). The related modular production process instructions generated as a result are forwarded to the lower levels of the automation pyramid, which utilise configurable production capabilities as they are described in section 2.3.1 (e.g. Simão, Stadzisz et al. 2006, Muckenhirn 2005). Within such hierarchical IT systems, each layer generally controls the configuration options available on the layer below, as shown in figure 2.7. This simplifies but also restricts the options available in higher level control systems.

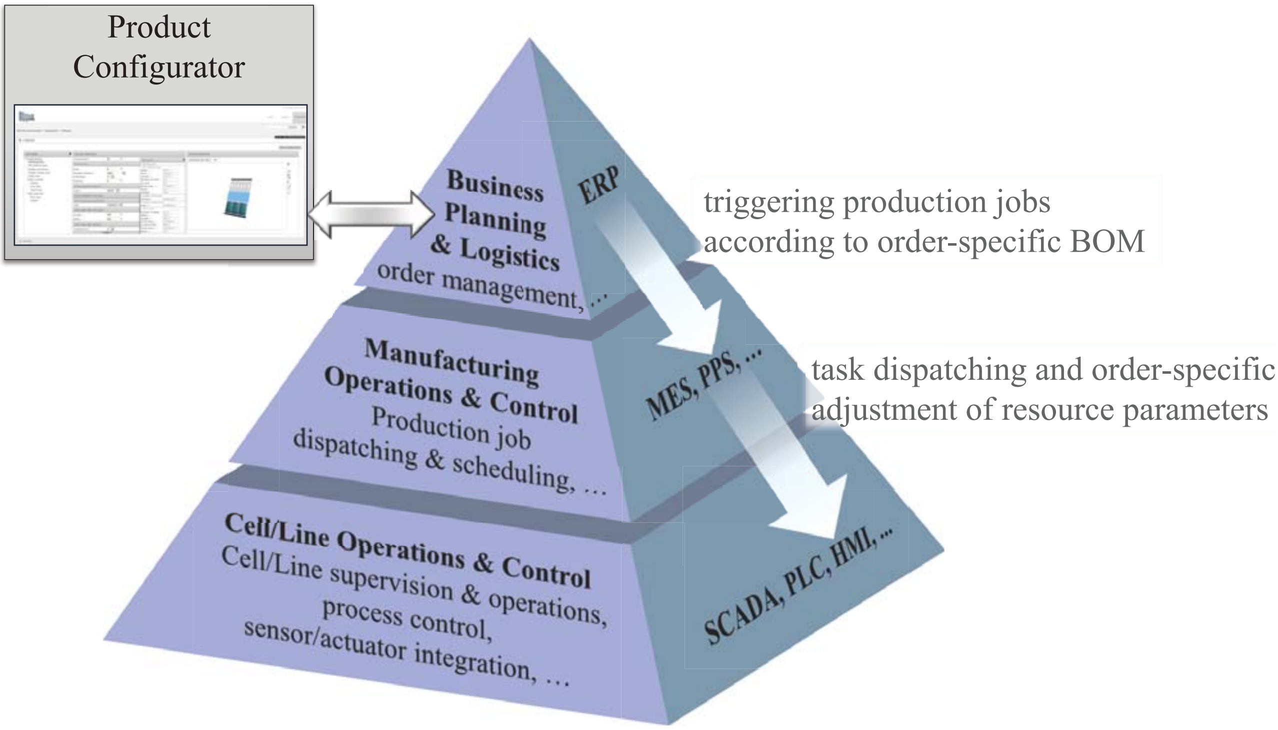

Figure 2.7. Overview of IT support for customised production

For personalised products which go beyond customisation based on pre-defined options, the degree of automation in manufacturing IT support is lower, since production system must be adjusted individually. This requires specific knowledge about processes and equipment which must often be supplied by experts. An exception to this are Computer Aided Manufacturing (CAM) systems which allow product designs to be translated automatically, e.g. numeric machine control programs (ISO 14649-10:2004).

2.5. Need for Research

The previous sections demonstrate that personalised production has the potential to make manufacturing companies from various industry sectors more competitive. To exploit this potential, the flexible integration of configurable manufacturing capabilities to agile production networks is required to be executed efficiently. However, current SCM methods and manufacturing IT infrastructures do not provide adequate support for this. Consequently, high management efforts and a lack of knowledge concerning available manufacturing capabilities and capacities prevent agile production networks from being beneficial.

To overcome these obstacles and simplify the configuration of agile production networks, an appropriate method for the customer-specific configuration of production networks, i.e. the combination of configurable manufacturing services, needs to be developed. Furthermore, an appropriate IT tool as single point of interaction is required to support the efficient application of the method.

As a first towards this, the main objectives and requirements, as well as essential success criteria, are identified in the following chapter.

3. Analysis of Conditions and Requirements

Based on the context set in the previous chapter, the following sections analyse the requirements on a method for personalised configuration and combination of manufacturing service in detail. In addition, specific conditions and requirements are derived which must be fulfilled to achieve the objectives explained in the following.

The creation of ad-hoc production network structures according to individual product specifications could improve both, the utilisation of manufacturing capacities and market access for the providers of manufacturing services. To support this, an appropriate method and the related IT system, which serves as single point of interaction and guides the service consumer as he implements the method, have to fulfil three major conditions: Production networks and involved manufacturing resources must be adaptable to customer-specific configurations, and the consumers of manufacturing services must be provided with the resulting personalisation options. Especially if end users having no in-depth knowledge of product, process, and production use the infrastructure to be established, and configure products on their own, the manufacturability of such products must be validated to ensure that the specifications developed are feasible. However, it is not only the validation of configurations which enables manufacturing service consumers to specify products individually. A knowledge management system, which reduces the know-how required for product configuration by reusing information about previous specifications, also contributes towards efficient and feasible product configurations. These main conditions that must be met by the method and IT tool for the configuration of agile production networks are summarised as follows:

`Obj01` **Support personalisation of products, i.e. related manufacturing services and their combinations**

`Obj02` **Ensure manufacturability of individually specified manufacturing service configurations and combinations**

`Obj03` **Reduce the required know-how and efforts for agile production network configuration**

Requirements addressing these objectives are derived for the domains of manufacturing services, supply chain and knowledge management by taking an argumentative-deductive approach as described by (Wilde and Hess 2007). This is applied based on typical application cases from production facility operation, personalised product and production network design, and the provision of manufacturing IT infrastructures, as well as the definitions from section 2.

3.1. Requirements on the Method

In the context of this thesis, methods are interpreted as guidelines, instructions, and recommended procedures to solve problems of a specific type, which serve as basis for systematic approaches in scientific and practical applications (Weller 2010, p. 36–37). Depending on application domains and objectives, various methods exist to achieve results in a structured way, e.g. for project management or software engineering, also in the context of production systems (cf. Patzak and Rattay 2014, Ludewig and Lichter 2013, Meier 2011). In most cases, these methods are based on models serving as tools to describe an objective, its context and conditions, in order to derive a solution to a specific problem. For the objectives of this work, the application of such a model-based approach – with a model representing knowledge about manufacturing capabilities and related conditions – is targeting. Accordingly, requirements regarding the development of model-based methods must be considered, as they are identified by Weller (2010, pp. 56):

`Req01` **Modelling**: The method shall describe the procedure of modelling, i.e. the description of the specific problem in an abstract way.

`Req02` **Model transformation**: The method shall describe the procedure of model transformation, i.e. the derivation of solutions from the modelled problem.

`Req03` **Model usage**: The method shall describe the procedure of model usage, i.e. the application of the derived solution in practice.

`Req04` **Modelling language**: The method shall define how the model must be described, i.e. it shall include the specification of a modelling language.

`Req05` **Integration of modelling language and procedure**: The modelling language must be integrated into the method, i.e. expressions have to be used as input or output of steps in the procedure.

3.2. Shareable Manufacturing Services

Manufacturers operating flexible production process facilities, such as machining or coating machines, additive manufacturing or (organic) semiconductor equipment, can provide their manufacturing capabilities and capacities to agile production networks without having to adapt their production equipment to each customer order at great effort. In doing so, they can exploit potential benefits of participating in production network, primarily increased capacity utilisation and market access, which apply especially to Small or Medium-sized Enterprises (SMEs) (Huspeninová and Homolka 2012).

Manufacturers can only participate in agile production networks if they share information about their manufacturing capabilities, thus making their facilities accessible to other network participants and potential customers. The information required includes technical details about processes, as well as capacities and lead times, which must be aligned with overall production objectives. Based on the exchange of this information, manufacturers are able to receive and execute orders in agile production networks. The requirements, which must be fulfilled to support this information exchange during the configuration of agile production networks, are explained in the following.

3.2.1. Configurable Manufacturing Service Characteristics

As visualised by figure 3.1, available customisation options are generally determined during product engineering on considering probable market trends. However, flexible production systems can usually address a larger range of customer preferences. When manufacturers supply manufacturing services to an agile pro-

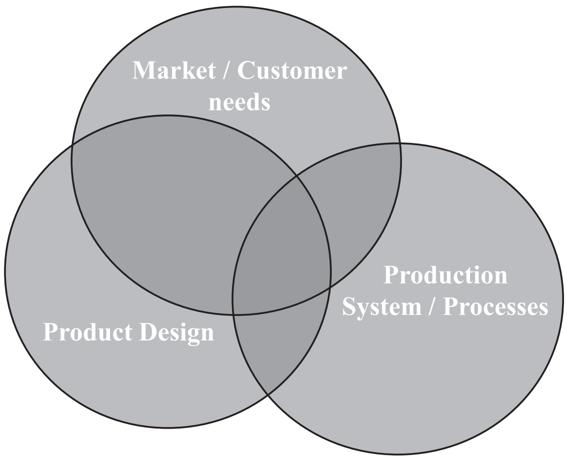

Figure 3.1. Actual customisation options derived from Bengtsson (2001)

duction network, they aim to overlap these three domains as much as possible in order to satisfy a maximum of customer preferences. A step towards achieving this objective is to provide the network with manufacturing options that are not restricted by product engineering, i.e. without pre-defining values and variants, but specified by process and product characteristics and their customisation options as they are available from the manufacturing facilities.

To achieve this, manufacturers must identify the characteristics of the executable manufacturing processes they intend to provide. These characteristics include the range of materials which can be processed and parameters restricting process results, e.g. maximum dimensions, as well as other parameters describing the execution of the production process. In addition, these process specifics must be mapped to the properties of potential process results, such as the surface characteristics of coatings to be applied, the geometries of products to be milled or drilled, and their optical appearance. This may also apply to parameters related to operational aspects of manufacturable output products, for instance energy consumption or load limits.

For each of the properties which can be adjusted to customers' needs, respective configuration options must be defined. These include valid ranges for parameter values, as well as available discrete values in cases where process and product characteristics cannot to be freely adjusted within a certain range, e.g. due to dependencies on input materials.

Besides the limitations of manufacturing equipment, the customisation options of manufacturing services may also be restricted by internal dependencies, i.e. parameters of product and process configurations affecting one another as visualised in figure 3.2. For example, the size of a coated areas may restrict the minimum coating thickness, and the colour and transparency of organic semiconductors have impact on their efficiency.

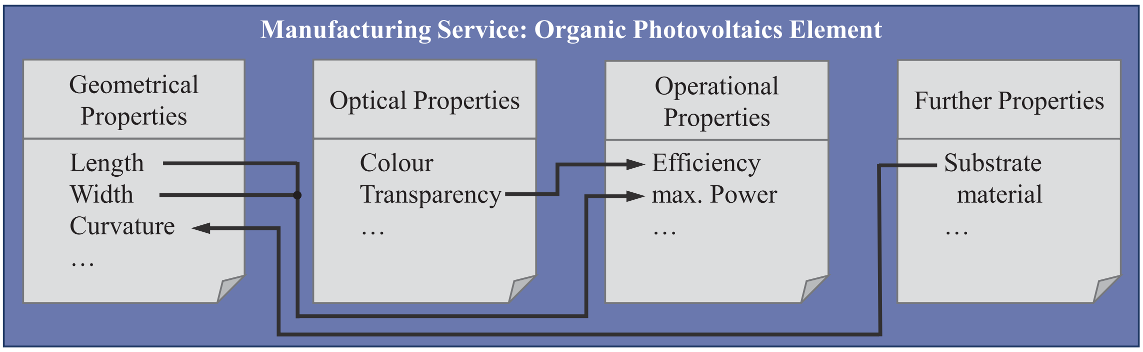

Figure 3.2. Examples of dependencies between the properties of manufacturing services

Knowledge of these dependencies must be shared, together with the characteristics and customisation options of manufacturing services, since they must be considered when specifying personalised products or processes in order to ensure their manufacturability.

Higher degrees product and process complexity increase administration efforts involved in modelling and publishing the entire range of product and process characteristics and their configuration options. To overcome this issue and remain cost effective, manufacturing service providers must adjust the level of detail of the manufacturing services they will provide. For instance, they can offer the capabilities of each single machine, or of an aggregated production line. In this context, manufacturers must also choose a suitable granularity for the product and process characteristics provided for customisation.

3.2.2. Availability of Capacities and other Contractual Information

If solely technical properties of manufacturing services are shared among production network participants, the execution of customer-specific orders is delayed by queuing times before each single manufacturing service is executed. This prevents customer orders from being fulfilled promptly and efficiently, an aspect which, together with product individualisation, essential for manufacturing companies to remain competitive (see section 2.1). To overcome this issue and reduce overall order lead times, additional information concerning the availability of manufacturing resources must be supplied to aid the planning and scheduling of order execution in agile production networks (cf. Stadtler 2005). This information includes details of available capacities, their current utilisation, and process lead times. Priorities caused by delivery dates and required capacities for other orders can be considered. Thus, low priority production jobs can be shifted to a later date to reduce lead times for new urgent ones.

In addition to the availability and lead times of manufacturing services, further information related to Service Level Agreements (SLAs), including costs for their execution, guaranteed product or process quality, and warranties, must be shared by manufacturing service providers to enable the selection of appropriate manufacturing services when configuring agile production networks.

Typically, these contractual details depend on the respective manufacturing resources but can also be influenced by the characteristics specified for the related product or process. For example, the lead time and quality of a coating process may depend on the thickness and material to be applied. Accordingly, the dependencies between manufacturing service characteristics described in section 3.2.1 can also involve properties related to SLAs.

In contrast to technical manufacturing service details as specified in section 3.2.1 and other SLA information which must be updated in parallel with production system settings, the availability of manufacturing services changes frequently with the progress of current production processes or the reception of new orders. Further SLA details can be calculated from data such as quality metrics or lead times, which are gathered from previously executed manufacturing orders and need be updated accordingly. However, updating the whole manufacturing service description with every order update makes it difficult to identify the updates resulting from production system reconfigurations which may affect existing product or process configurations. For this reason, information related to the availability of manufacturing services must be described and made known separately in order to address the different update cycles.

3.2.3. Accessibility of Manufacturing Service Information

As soon as a manufacturer has specified a manufacturing service as described in sections 3.2.1 and 3.2.2, to make the manufacturing service utilisable beyond factory boundaries he must share the related information with potential customers or other production network participants. In doing so, the manufacturing service information will be processed by IT systems, which also handle information about manufacturing services from various other sources. Therefore, manufacturing services must be described in a machine-readable format with contents arranged in a defined structure in order to allow other network participants to interpret and utilise them. Such a format and structure also serve as syntax for a manufacturing service description language as required according to **Req04**, since these provide a framework to model knowledge about processes, products, and their personalisation options.

In addition to being described with a generic structure, manufacturing service information must be distributed to customers and production network participants to make it utilisable. Since searching separately for relevant information about each manufacturing service provider's capabilities would involve high efforts, it is preferred to provide manufacturing service descriptions via an electronic marketplace or common index (cf. Bakos 1991). In this context, it must be considered that the implementation of such a common access point requires the description of manufacturing services to be extended by information about their providers so that requests from customers can be directed to the origin of the manufacturing service.

3.2.4. Derived Requirements on Manufacturing Services

From the considerations above, the following requirements related to the provision of manufacturing services have been derived:

`Req06` **Manufacturing service model**: Manufacturing services must be represented by a model describing the properties of their related processes and products by means of a generic structure.

`Req07` **Parameterisation**: The manufacturing services and their models shall reflect the ability to personalise product and process characteristics within the boundaries set by related manufacturing resources.

`Req08` **SLA information**: In addition to technical manufacturing service characteristics, i.e. product and process parameters, the manufacturing service description shall include contractual information, primarily costs, lead times, and warranties.

`Req09` **Dependencies between manufacturing service parameters**: When configuring manufacturing services, the potential impact of specific parameter settings on other manufacturing service characteristics must be considered.

`Req10` **Level of detail of manufacturing services**: The granularity of the details of a specific manufacturing service must be adjustable to suit the manufacturer's preferences.

`Req11` **Availability of manufacturing services**: In addition to statically modelling the technical and contractual properties of manufacturing services, their availability must be represented by a complementary model which allows frequent updates.

`Req12` **Common access point for manufacturing services**: Manufacturing service information must be accessible to customers and other production network participants via a common index or market place.

3.3. Designing Agile Production Networks

Personalised product specification and the related configuration of agile production networks contribute to an improved customer satisfaction. End-customers or product designers can develop or adapt products to suit their individual needs by selecting, configuring, and utilising respective manufacturing services, i.e. related products, components, and processes. Consequently, they can design and manufacture products without having own facilities. In many cases, however, manufacturing services do not deliver an end-product but rather contribute towards its manufacture. For instance, the service for manufacturing customer-specific organic semiconductors must be combined with services providing appropriate frames and electrical connections in order to obtain a lighting element whose colour, transparency, and shape have been tailored to a customer's preferences. In other words, manufacturing services must generally be arranged into product trees or process chains while utilising them for the production of personalised goods.

3.3.1. Comparability of Manufacturing Services

When customers select manufacturing services for integration into a specific agile production network tailored to their ideas and needs, they must analyse their available product or process characteristics as described in section 3.2.1. To select the best manufacturing service alternatives to fulfil their preferences, customers must also assess criteria such as costs, potential lead times and other SLAs, which may also include experience from the execution of previous orders (see section 3.2.2).

Customers can select manufacturing services based on their own product and process know-how, or by referring to suggestions gained from previously existing configurations. In doing so, the understandability and thus comparability of manufacturing service descriptions must be ensured in order to avoid misunderstandings between different companies and industry sectors (Matzner and Becker 2012). This is aided by the application of a generic description structure as defined in section 3.2.3.

Beyond this, the meanings of the contents of manufacturing service descriptions must be aligned with one another. This can be achieved by classifying the properties of manufacturing services, i.e. by assigning related processes, products, and characteristics to categories. Additionally, the comparability of manufacturing services can be facilitated by applying semantic technologies, which help to translate terms and definitions across different domains. This is essential if different industrial sectors or companies use different terms for the same facts or, vice versa, if domains use the same words to refer to different meanings.

3.3.2. Linking Manufacturing Services

Once appropriate manufacturing services have been selected by customers or product designers, they must be connected to form product trees or process chains which represent the end-product's route through the production network. To orchestrate services in general, the output of one or more services is connected to the input of the subsequent service, which results in a directed process structure (cf. Reichert and Weber 2012, p. 60). This approach is also suitable for combining manufacturing services, whereby the output of a manufacturing service, i.e. the resulting product, is specified as input for another manufacturing service in order to create the required production network structure.

In doing so, three kinds of dependencies between combined manufacturing services must be considered (see also figure 3.3):

1. Dependencies between manufacturing services in general: These dependencies shape the structure of product trees or process chains, including alternative manufacturing services and the number of components to be integrated.

2. Dependencies related to the application conditions of processes and resulting products: When connecting manufacturing services to create a sequence of process steps, these steps may require specific pre-conditions to be fulfilled with regard to product components, materials, or previous process steps. In the semiconductor industry, for example, etching and doping processes usually only make sense if the structure to be applied has been prepared in advance by photoresist coating and lithography.

3. Dependencies between the characteristics of combined manufacturing services: When products are manufactured by integrating supplying processes and sub-products, their properties are influenced by the characteristics of the respective components implemented. Vice versa, the specification of a component manufacturing service must reflect the needs of the final product towards it is contributing. For instance, the size and shape of a photovoltaic module must be aligned with the size and shape of wafers requiring assembly, as well as their position on the glass substrate.

Single manufacturing services can be used to implement various individual product and process specifications, and therefore need to be integrated into various combinations of manufacturing services. Accordingly, the dependencies defining the structure of the product tree or process chain, and thus the related production

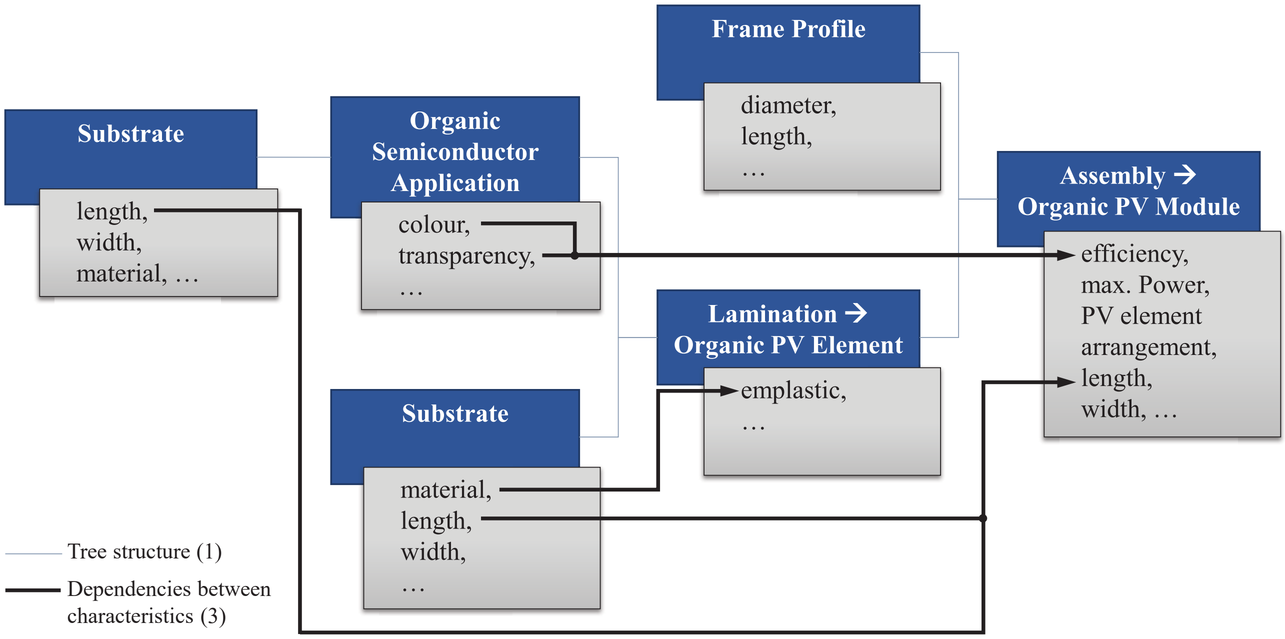

Figure 3.3. Example of a product / process tree and dependencies between the characteristics of related manufacturing services

network, are only established when combining manufacturing services, i.e. independently of manufacturing service descriptions.

In addition to this, dependencies between manufacturing services, which are related to their application conditions and characteristics, are not only specified by pure connections established by customers and product designers, but also rely on pre-defined knowledge of manufacturing service details. To consider this knowledge, i.e. to represent conditions which apply to the connections established, dependencies must include rules which not only interlink input and output manufacturing services or parameters, but also express semantic or logic details of those relationships (e.g. Loskyll, Schlick et al. 2011). For dependencies related to the application of manufacturing services, these rules must define conditions based on product or process categories. Dependencies between the characteristics of combined manufacturing services must reflect parameter restrictions along product trees or process chains. Related rules must indicate the impact of the properties of a certain parameter on the characteristics of previous or subsequent manufacturing services. For example, the dimensions of glass substrates produced by a respective manufacturing service affect the dimensions of related lighting elements which are assembled in a follow-up manufacturing service (cf. figure 3.3).

3.3.3. Derived Requirements for Combining Configurable Manufacturing Services

The following requirements for connecting manufacturing services are derived from the analyses described above:

`Req13` **Comparability of manufacturing services**: Manufacturing service descriptions must be comparable. This is achieved by a generic structure, as well as by classifying processes, products, and their characteristics, and applying semantic technologies.

`Req14` **Dependencies between manufacturing services**: Three kinds of dependencies between manufacturing services must be considered when linking them: Dependencies structuring the product tree or process chain, dependencies related to application conditions, and dependencies between manufacturing service characteristics.

`Req15` **Expression of dependency rules**: Dependencies related to application conditions and manufacturing service characteristics must not only establish links, but also be able to represent rules expressing the impact of a specific manufacturing service configuration on the details of connected manufacturing services.

`Req16` **Complementary model for dependencies between manufacturing services**: Since it must be possible to reuse manufacturing services for different customer-specific configurations, the links to establish product trees or process chains must be represented by means of a separate, complementary model.

3.4. Knowledge in Agile Production Network Configuration

The formulation of dependencies related to the characteristics of manufacturing services requires extensive product and process know-how. Since only few customers and product designers are experts in all related fields, additional measures are required to enable them to specify products tailored to their individual needs with an acceptable amount of work. The implementation of a knowledge base, which serves as common repository for previous experiences and existing solutions, addresses this need, since it allows previously gathered knowledge to be exploited. Figure 3.4 illustrates the impact of such a knowledge base on learning cycles related to product and production network configuration, which are analogous to those for reconfiguring factory-internal production systems as they are described by Berger, Mangold et al. (2009).

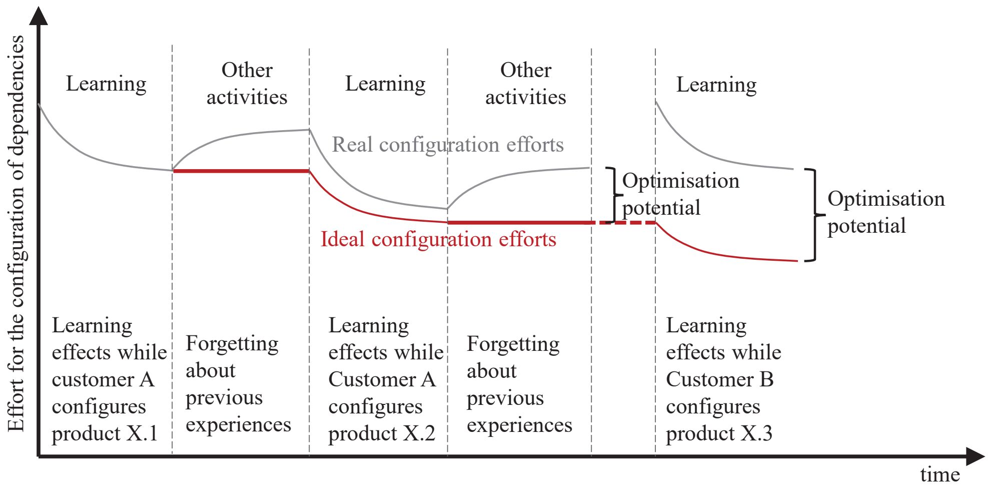

Figure 3.4. Impact of available knowledge on agile production network configuration efforts derived from Berger, Mangold et al. (2009)

Since customers wishing to receive personalised products tend to configure and arrange related manufacturing services only once, the learning effects generated from the experience of a single user are not suitable for extending the knowledge base for agile production network configurations. However, since customer-specific configurations are developed in an environment where other participants are executing similar tasks, i.e. specifying products and processes, learning effects can be gained from the related community (cf. Argote 2013).

3.4.1. Suggestion and Validation of Links between Manufacturing Services

The application of a knowledge base aims at simplifying the configuration and combination of manufacturing services, i.e. reducing related efforts and enabling non-experts to create of personalised product specifications. In this context, it would be beneficial for customers who are configuring products and related production networks if suitable links between manufacturing services were suggested. These suggestions of dependencies could be reasoned from previously defined agile production networks on analysing the connections between manufacturing services contained, as well as their characteristics, and categories.

In addition to suggesting dependencies for manufacturing service configuration and combination, appropriate validation methods based on existing knowledge can serve as tool to assess the manufacturability of defined products. Besides considering manufacturing service characteristics and their limitations, manufacturability must be ensured by means of completely and correctly configured dependencies. To verify the completeness and feasibility of established dependencies between manufacturing services, knowledge from previously configured and successfully executed manufacturing service combinations must be applied to these newly-configured connections.

In doing so, suggestions and validations must cover all the kinds of dependencies described in section 3.3.2. This requires the provision and application of knowledge related to relationships between the process, product, and parameter categories of connected manufacturing services, as well as between specific values of manufacturing service characteristics which could affect resource- and process-related restrictions within a dedicated manufacturing service (see also requirements `Req09`, `Req14`, `Req15`).

3.4.2. Extension and Optimisation of the Knowledge Base

As mentioned beforehand, the suggestion and validation of potential dependencies between manufacturing services can contribute to improving the quality of future manufacturing service combinations and to reducing the efforts involved. Since these suggestions and validations are derived from knowledge about previously defined manufacturing service combinations, their quality strongly depends on the quantity and quality of already established connections between manufacturing services. To address this issue, the knowledge base must be continuously updated and extended with newly created dependencies as shown in figure 3.5.

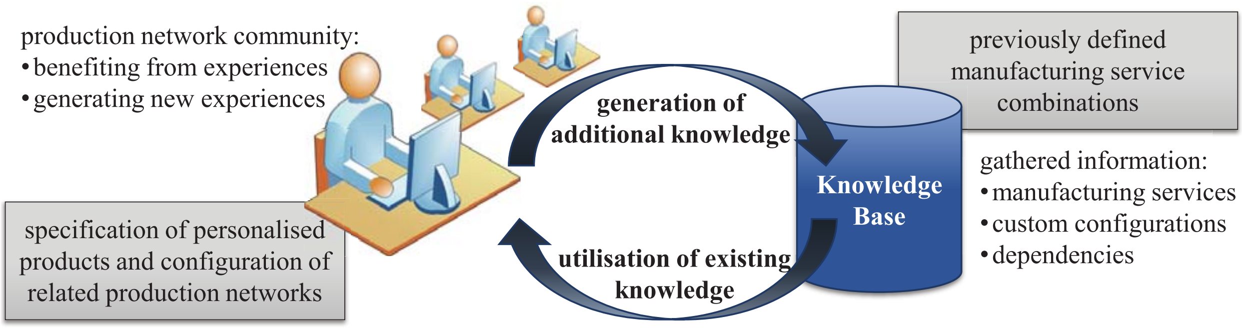

Figure 3.5. Knowledge generation and utilisation cycle

As efficient knowledge gathering is essential to develop and maintain an extensive and detailed knowledge base (Argote 2013, p. 8), application barriers, mainly additional efforts involved in knowledge modelling, must be avoided during interaction with customers who generate and use the knowledge. Consequently, knowledge should be gathered automatically during product specification and configuration of the related product tree or process chain.

In addition, it is necessary to structure the gathered knowledge about dependencies in order to make it available for further usage and automated handling (see also section 2.2.3). Together with the application of semantic technologies and classifications for generating and processing knowledge about dependencies, a common structure for representing dependencies aids the consistent interpretation of facts (see also requirements `Req04`, `Req13` and `Req16`).

3.4.3. Derived Requirements for Knowledge Utilisation

Considering the application of knowledge management to the combination of manufacturing services results in the requirements listed below:

`Req17` **Knowledge gathering**: Knowledge about the feasibility of manufacturing service combinations must be gathered from previously defined agile production networks, i.e. by analysing existing dependencies.

`Req18` **Support with configuring and combining manufacturing services**: Suggestions of dependencies, as well as related validation and verification functionalities should be derived from the gathered knowledge and supplied to customers in order to support efficient product specification and ensure the manufacturability of configured products.

`Req19` **Extensibility of the knowledge base**: The knowledge base for storing previously defined combinations of manufacturing services must be extensible in order to increase the amount of available information and continuously improve related analysis results.

3.5. Industrial Success Criteria

Besides the requirements described in sections 3.1 to 3.4, the method and model together with their application have to fulfil further requirements to ensure acceptance of the solution by the providers and customers of manufacturing services. However, since the focus of this work is on research, these requirements do not need to be fully implemented by the intended solution. It suffices that developments are enabled to be easily extended by the respective features.

3.5.1. Integration with Business Processes and IT Infrastructures

To maintain the efficiency of their business operations, manufacturing service providers must align the provision and execution of manufacturing services for agile production network with their internal business processes and IT infrastructures. To do this, several interfaces must be considered as shown in figure 3.6. In partic-

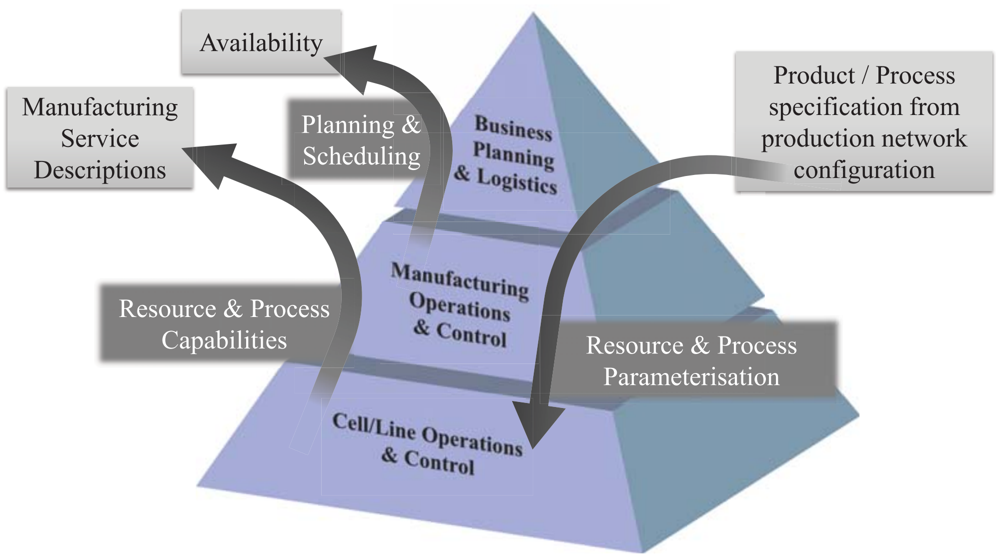

Figure 3.6. Interfaces to business processes and IT systems

ular, manufacturing capabilities must be extracted from existing infrastructures in order to publicise manufacturing service descriptions. Available capacities must be forwarded from factory-internal planning and scheduling systems to the production network management, from where orders including related product or process specifications are received and transferred to internal order management, planning and scheduling systems, before individually configured production processes are executed.

The manual execution of these activities by manufacturing service providers is time-consuming and prone to error, especially where complex information is concerned. The automated extraction and transfer of information counteracts these issues and ensures that manufacturing service details are kept up-to-date at production network level. It also ensures that related information is exchanged effectively, especially in cases where data must be updated frequently as it applies to the availability of capacities.

From the customer's perspective, the configuration and combination of manufacturing services should be integrated into product design tools. Thus, product specification and agile production network configuration processes would not have to be performed independently from each other, but rather concurrently with reduced complexity or effort. To do this, the respective user interfaces for product specification must integrate capabilities for both, customisation and manufacturing service combination. This can be achieved, for example, by providing functionalities for editing parameters and linking manufacturing services in a simple, text-based form, as well as by integrating them into graphic-based product configurators.

When integrating models for manufacturing services and their dependencies, which also serve as a format for transferring information to production network management systems, into existing IT infrastructures, integration efforts strongly depend on the degree of standardisation of related interfaces and data structures (Rauschecker, Stock et al. 2014, Loukis and Charalabidis 2013). Consequently, the solution to be developed should be compatible with existing standards established for product and process description and categorisation, as well as for the exchange of business information.

3.5.2. Acceptance Criteria

To ensure that the method and model to be developed, including their implementation by an IT system, not only provide all the functionalities required for the customised configuration of agile production networks, but are also accepted by customers and manufacturing service providers for application in practice, further conditions must be fulfilled (cf. Ullrich, Vladova et al. 2015).

The related IT systems must be secure, since concerns about potential unauthorised access to know-how and other confidential information is one of the main obstacles encountered when implementing IT systems across company boundaries.

Furthermore, the solution must address availability, connectivity, and robustness in order to process user interactions reliably and promptly. For instance, feedback on availability and manufacturability requests for manufacturing services and their combinations must be delivered online within a reasonable response time. A further related requirement is usability, i.e. user-friendly interfaces for interaction with human applicants which allow the system to be used intuitively.

3.5.3. Derived Requirements Related to Applicability

From the considerations above, the following requirements regarding the industrial applicability of the method, model, and IT system are derived:

`Req20` **Integration into factory-internal processes and infrastructures**: The manufacturing service model must extractable from factory-internal systems. Reversely, manufacturing service specifications and orders must be able to be submitted to these systems.

`Req21` **Integration with product and process design**: The configuration and combination of manufacturing services, including related IT functionalities, should be integrated into tools for the specification of product and process details.

`Req22` **Compatibility with existing standards**: To reduce integration efforts, the model and system must integrate applicable existing standards.

`Req23` **IT security and privacy**: To achieve acceptance for the solution, protection against unauthorised access to know-how and other confidential information must be guaranteed.

`Req24` **Responsiveness and usability**: System interfaces, especially with users, must allow interruption-free and intuitive interaction.

3.6. Summary of Requirements

The requirements identified in this chapter are summarised below. They can be classified into two groups: requirements on the method and its application, and requirements on the model, its development, implementation, and usage in the related IT system.

Source	Req. no.	Requirement	Priority
Method objectives	`Obj01`	Support personalisation of products	mandatory
	`Obj02`	Manufacturability assessment	mandatory
	`Obj03`	Reduction of know-how and efforts involved in the configuration and combination of manufacturing services	mandatory
Method characteristics	`Req01`	Description of modelling procedure	mandatory
	`Req02`	Description of model transformation	mandatory
	`Req03`	Description of model usage	mandatory
	`Req04`	Modelling language	mandatory
	`Req05`	Integrated modelling language and procedure	mandatory
Method implementation	`Req20`	Integration into factory-internal processes and infrastructures	recommended
	`Req21`	Integration with product and process design	recommended
	`Req22`	Compatibility with existing standards	recommended
	`Req23`	IT security and privacy	recommended
	`Req24`	Responsiveness and usability	recommended

Table 3.1. Summary of method objectives and requirements

Domain	Req. no.	Requirement	Priority
Provision of manufacturing services	`Req06`	Manufacturing service model	mandatory
	`Req07`	Parameterisation	mandatory
	`Req08`	SLA information	mandatory
	`Req09`	Dependencies between manufacturing service parameters	mandatory
	`Req10`	Flexible level of detail for manufacturing services	recommended
	`Req11`	Online availability of manufacturing services	recommended
	`Req12`	Common access point for manufacturing services	recommended
Configuration of agile production networks	`Req13`	Comparability of manufacturing services	mandatory
	`Req14`	Definition of dependencies between manufacturing services	mandatory
	`Req15`	Expression of dependency rules	mandatory
	`Req16`	Separate, complementary model for dependencies	mandatory
Utilisation of knowledge	`Req17`	Gathering knowledge from existing configurations	mandatory
	`Req18`	Derivation of suggestions and feasibility assessment for dependencies	mandatory
	`Req19`	Extensibility of the knowledge base	mandatory

Table 3.2. Summary of requirements on the model and system

4. Related Research

To address the challenges associated with freely configuring agile production networks based on manufacturing services identified in sections 1.2 and 2.5, efforts have been made in several relevant fields of research. This chapter gives an overview of the state of the art in these fields of research, allowing specific research gaps regarding the configuration of agile production networks to be identified. An emphasis was placed on analysing existing work which focuses on the modelling and combination of customisable manufacturing services, including measures to utilise knowledge. Furthermore, the application of these models and measures in existing methods and systems to configure and manage agile production networks has been investigated.

4.1. Description of Manufacturing Services

Models of manufacturing services have to cover several properties of related products and processes. As explained in sections 3.2.1 and 3.2.2, this includes product and process information, their customisation options, and SLA details. This section outlines current measures to model these data.

4.1.1. Product-Based Models

Personalised product specifications are usually exchanged among production network stakeholders based on Computer Aided Design (CAD) data. To ensure the transferability of this information throughout the product lifecycle, as well as across organisational boundaries, standardised data formats have been established to describe product models. One of the most commonly used standards in this context is the Standard for The Exchange of Product model data (STEP), which is defined by ISO 10303-41 (Rudolph and Dietrich 2003).

It defines a standardised description language for product data in order to represent universal product characteristics and their interrelationships, including geometric definitions based on points, lines, and direction vectors (Anderl and Trippner 2000, pp. 54–64, 71–74). Similarly, other widely used standards such as the Drawing Interchange Format (DXF), Initial Graphics Exchange Specification (IGES), or Jupiter Tessellation (JT) also specify the representation of geometric objects (Stoye, Vornholt et al. 2011). However, depending on the kind of product, industrial sector, and objectives for which information needs be exchanged, product descriptions must consider additional product characteristics and representation requirements. For this reason, ISO 10303-41 defines several Application Protocols (APs) which include basic models for specific industrial sectors or phases of product lifecycles. Examples for these specific models are 2D or 3D designs, process plans for machining, and assembly models. Furthermore, specific APs also exist for automotive, furniture, or electrotechnical applications (SCRA 2006).

4.1.2. Manufacturing System Descriptions

The properties of a certain result of a manufacturing process are determined by the underlying production system, including machines, tools, and program settings which implement product specifics, as well as by the materials processed (Groover 2010, pp. 6–7). Accordingly, languages representing sharable manufacturing capabilities to be used across system boundaries must model these characteristics and their interrelationships (Ameri, Urbanovsky et al. 2012). Various manufacturing system models reflect this by defining ontologies which integrate system, process, and product details (Negri, Fumagalli et al. 2016). An example for such an information structure for a manufacturing system description is shown in figure 4.1. Usually, the information contained is further detailed by extending these models with data structures for machine component features, process parameters and control messages, as well as material and product characteristics (e.g. Hoffmeister 2013, Loskyll, Schlick et al. 2011).

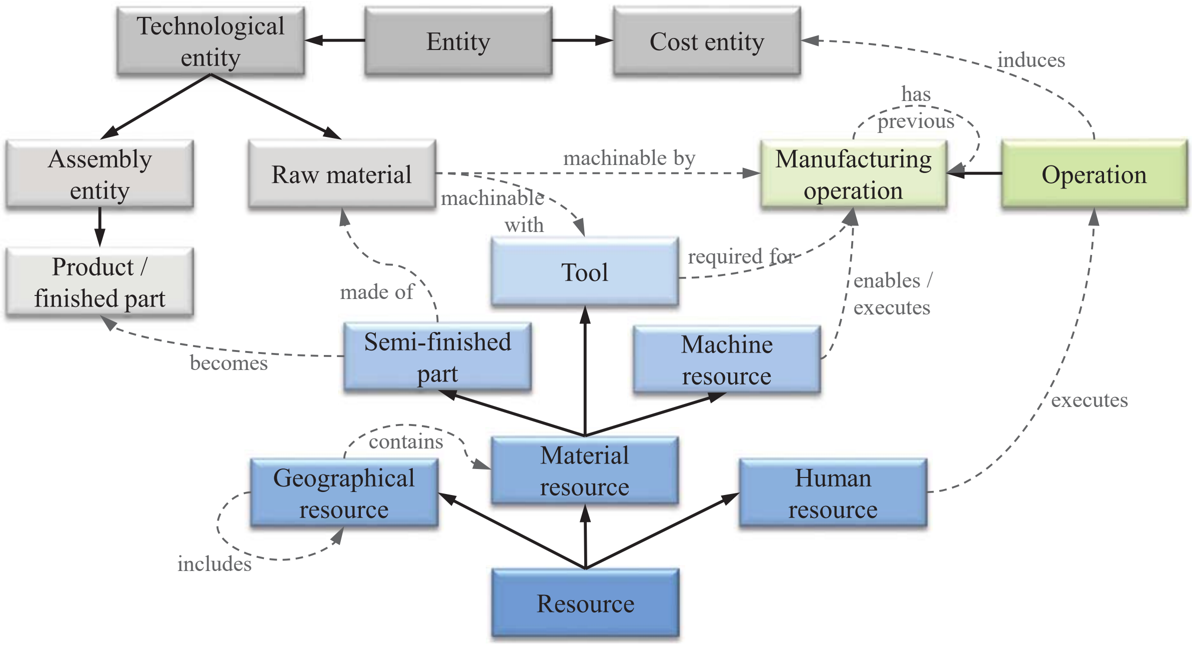

Figure 4.1. Ontology for manufacturing capabilities according to Lemaignan, Siadat et al. (2006)

In many cases, the application of manufacturing system descriptions aims at implementing "plug and produce" concepts, i.e. at decreasing reconfiguration efforts and ramp-up times for modular manufacturing systems (cf. Konrad 2012, Lohse, Hirani et al. 2005), or at the dynamic configuration and integration of production networks (cf. Ameri and McArthur 2013, Markaki, Panopoulos et al. 2013). In both cases, manufacturing process descriptions enable the fast and low-effort integration of manufacturing systems to higher level systems.

A common approach to implement manufacturing service descriptions is integrating respective ontologies into standardised formats. For instance, Ameri and McArthur (2013), Yan, Ye et al. (2010), and Lemaignan, Siadat et al. (2006) describe manufacturing process descriptions based on OWL, while Loskyll, Schlick et al. (2011), Cai, Zhang et al. (2011), and Jang, Jeong et al. (2008) extend the service description standards Web Services Description Language (WSDL) and

Universal Description, Discovery and Integration (UDDI) with semantic annotations.

4.1.3. Representation of Contractual Information

Besides functional and technical information, manufacturing service descriptions need to provide information about conditions for their utilisation. To do so, the Unified Service Description Language (USDL), which defines a generic framework for the description of services, contains pricing, legal, and service level modules to provide information such as cost models, general terms and conditions, warranties, and execution times (Barros, Oberle et al. 2012). However, USDL does not provide common semantics, but only defines a structure for descriptions which can also be partially filled with free text. Thus, to enable comparability and support for automated information processing, additional data models and IT tools must be applied to USDL documents.

To process information about service conditions automatically, machine-readable modelling languages as they are applied in the IT domain have to be utilised. For SoAs, Keller and Ludwig (2003) specify a Web Service Level Agreement (WSLA) language which defines Extensible Markup Language (XML) structures for SLA parameters and their monitoring. When setting up an SLA model for software systems, relevant properties such as reliability, performance efficiency, and accessibility are usually implemented based on the common system and software quality models specified in ISO/IEC 25010:2011.

Description contents for software SLAs focus mainly on related Quality of Service (QoS) criteria, whose parameters differ from those of manufacturing services and hardly cover costs and legal aspects. Therefore, when designing respective models for the manufacturing domain, the above-mentioned concepts for describing contractual information must be transferred and extended. In manufacturing, contractual models focus usually on logistics requirements as they are identified in section 2.2.2. This means that they include information about product quantities, quality objectives, and delivery times. Relevant examples of such information are the findings of Shepherd and Günter (2011) and Seth, Deshmukh et al. (2006), who define attributes to be considered for supply chain performance and quality measurement. Tao, Zhang et al. (2012) combine both approaches by integrating information about manufacturing service performance and quality into one manufacturing service ontology.

4.1.4. Configurability of Manufacturing Services

If manufacturing services can be customised to individual needs, their properties, i.e. related product details, must be configurable. Feedback to customers, e.g. in the form of a graphic representation of the resulting products, improves usability. The ability to parameterise the underlying models is a necessary precondition to update such representations according to the configuration. This is provided by ISO 10303-108, *Parameterisation and constraints for explicit geometric product models*. It extends STEP with variable parameters and explicit boundary conditions, which are modelled as rules and links to other data elements (Pratt, Anderson et al. 2005).

Since customer interaction rarely takes place via special professional tools, the application of a format which can be easily integrated into web interfaces would save data transfer or integration efforts. Extensible 3D (X3D) is an XML-based format for representing 3D models (Brutzman and Daly 2007) which fulfils this requirement. However, parameterisation is not integrated into that standard by default. Consequently, application-specific extensions must be implemented to integrate configurable product specifications to X3D as Yip, Corney et al. (2013) did by combining configuration and visualisation engines.

In addition to the parameterisation of product models, related production process representations need to reflect equivalent configurability in order to ensure that the respective customised specifications can be implemented. To address this, there are production system and process descriptions which integrate parameterisation capabilities. For instance, most of the process descriptions which also fulfil requirements from section 4.1.2 already include meta models for configurable process parameters and related production system limitations (cf. figure 4.2, Rauschecker and Stöhr 2012, Bengel 2010).

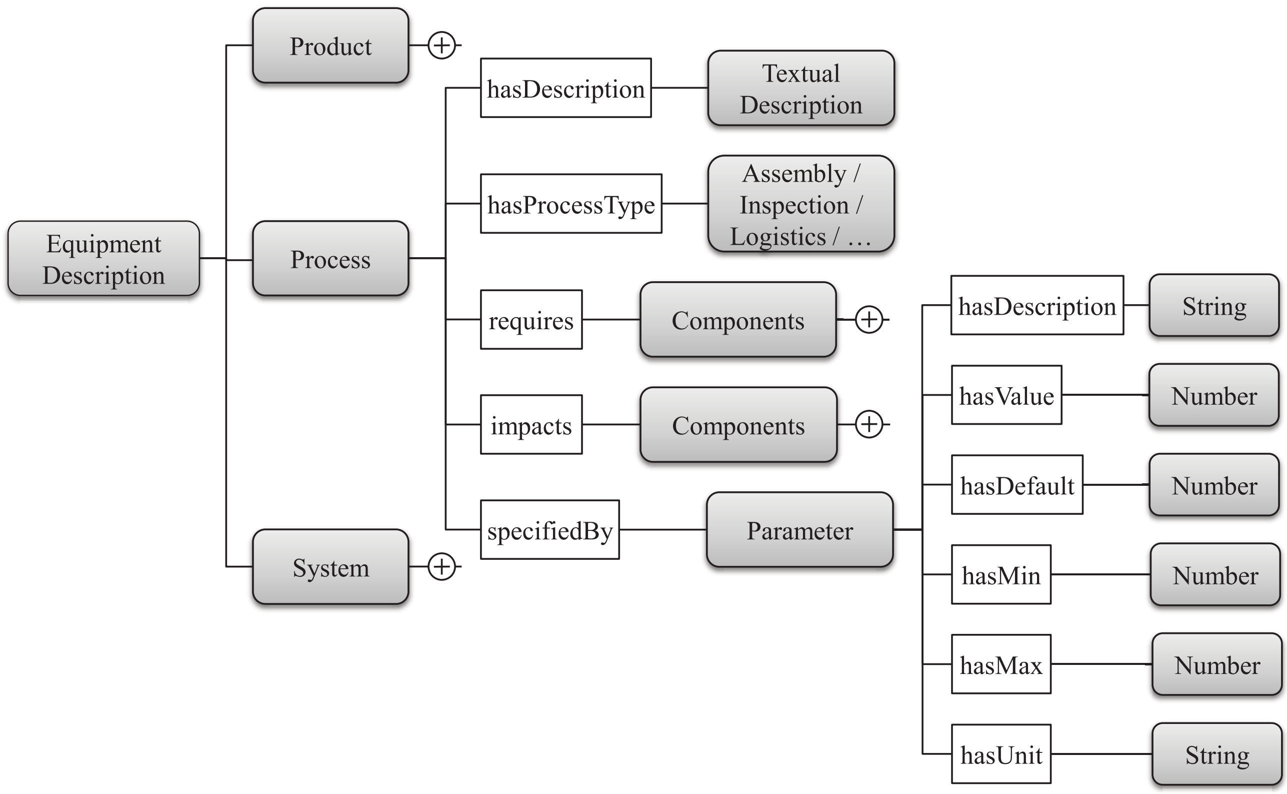

Figure 4.2. Manufacturing process description according to Konrad (2012)

Besides these manufacturing process ontologies, standards exist for equipment self-description, which also include data structures for parameterising related processes. For instance, the Semiconductor Equipment and Materials International (SEMI) standard E139, *Specification for Recipe and Parameter Management (RaP)*, and the Standardisation in Lab Automation (SiLA) *Device Control and Data Interface Specification* both define generic data structures for equipment recipes or command parameters, which potentially include variables, as well as their invocation to higher-level production management systems.

Like production system and process descriptions, most SLA models include parameterisation capabilities by default. The WSLA specification, for instance, defines parameters and related measurement metrics for specific properties such as response times or transaction rates, which need to be detailed during service instantiation (Keller and Ludwig 2003). The USDL models for contractual aspects of services also provide respective structures for describing parameters (Kiemes, Novelli et al. 2012, Marienfeld, Höfig et al. 2012). For example, these enable payment or discount options to be selected, or variable service level attributes to be defined. However, in the manufacturing context, those options can usually not be configured independently, since they are affected by related product specifications to a large extent.

4.2. Classification of Manufacturing Services

To establish comprehensibility and comparability of manufacturing services across distributed production networks, relevant ideas and objects must be categorised, i.e. identified, differentiated according to common patterns, and grouped into respective classes according to their specific properties (Harnad 2005). The following sections describe existing approaches from the manufacturing domain which can be applied to achieve this.

4.2.1. Categorisation Approaches

The properties used in order to categorise manufacturing services are the specifics of the products and processes they provide. Several manufacturing service descriptions reflect this in their model structure by containing category elements. These elements are filled with simple data elements, ontology contents, or references to classification models (cf. Lu, Shao et al. 2014, Tao, Zhang et al. 2012). In doing so, the associated ontologies and classification models represent the branched structure of category hierarchies, as shown by the example in figure 4.3.

Additionally, there are further classification approaches which do not define fixed category hierarchies, but provide data structures and options for flexibly allocating categories of production processes (cf. Giess, McMahon et al. 2009, Dulmet, Lhote et al. 2002).

The category trees resulting from these classification approaches serve the standardsation of manufacturing service classifications throughout their whole ap-

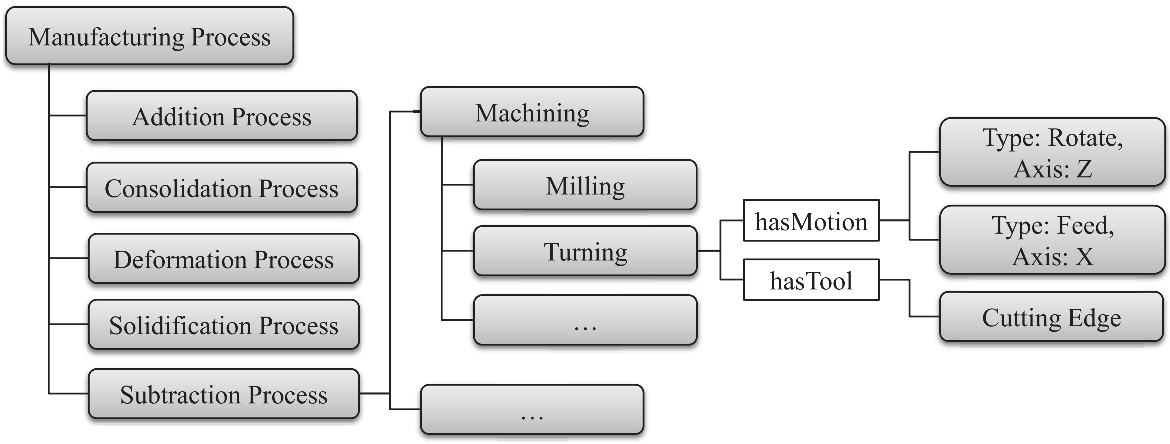

Figure 4.3. Classification of manufacturing processes extracted from Ameri, Urbanovsky et al. (2012), Ameri and Patil (2012)

plication context, thus improving related search mechanisms and comparability. However, standardised definitions of manufacturing service categories within specific application boundaries are not sufficient if manufacturing services are shared across those boundaries, e.g. among different enterprises in a production network. Consequently, further-reaching standardisation schemes are necessary.

4.2.2. Relevant Standards

Various standards exist that are applicable to the categorisation of manufacturing services. They can be differentiated according to the manufacturing service properties concerned. Classification standards which describe industrial sectors can be used to set the context for manufacturing services, i.e. to categorise their providers' activities, while standards specifying product or manufacturing process categories further detail manufacturing service capabilities. Table 4.1 lists some examples of classification standards which serve these purposes.

Scope	Standard
Industry sectors	Statistical Classification of Economic Activities in the European Community (Nomenclature statistique des activités économiques dans la Communauté européenne, NACE), which largely overlaps the International Standard Industrial Classification (ISIC) because it is based on it.
	North American Industry Classification System (NAICS), the equivalent to NACE in North America.
Products	Central Product Classification (CPC), a United Nations standard which categorises products according to their industrial origin.
	Classification of Products by Activity (CPA), the European version of CPC, which is also defined by the United Nations Statistical Division (UNSD).
	Global Product Classification (GPC) which is initiated by the GS1 consortium.
	TVarious industry-specific standards, such as IEC 61360-4:2005 DB,*Common Data Dictionary (CDD)*, or ISO 22745-1:2010, *Open technical dictionaries and their application to master data*, which is implemented by the Electronic Commerce Code Management Association (ECCMA) Open Technical Dictionary (eOTD), RosettaNet Technical Dictionary (RNTD), or eCl@ss, driven by electrical, electronics, and semiconductor industries.
Production processes	DIN 8580:2003-09 and related "Manufacturing Processes" standards which detail manufacturing processes categories such as forming, separating, joining, or coating.
	The Unit Manufacturing Process Taxonomy as it is defined by the US National Research Council (1995).
	Guidelines, especially the VDI manuals on manufacturing processes (VDI 2015) describe single categories in more detail and provide common terms and definitions for their implementation.

Table 4.1. Relevant standards for classifying manufacturing services

In total, there are more than 700 industry, product, and process classifications (Royere, Haas et al. 2014), which are initiated by national or international, universal or industry sector and application specific associations and interest groups. Most of them are structured hierarchically, i.e. each item is linked to one specific parent item. Some of these standards not only define terms and hierarchies, but also supply the related model for their description. For instance, GPC and RNTD provide respective XML schemes.

4.3. Combination of Services

To combine manufacturing services, relevant approaches from two domains can be taken: Service-oriented IT systems provide support for automatically generating and executing IT service bundles, while solutions for configuring and combining manufacturing systems consider the specific needs of on-demand production.

4.3.1. Orchestration of IT Services

Core concepts of SoAs are modularity and reusability of services (Josuttis 2008, p. 42). As a result, applications which cover whole business processes can be aggregated from modular and reusable components. For instance, an order execution service integrates customer and warehouse management services to organise product delivery. In parallel, these services could also be used for marketing activities or inventory management. Cloud computing solutions which provide IT services via Software-as-a-Service (SaaS) infrastructures increase the need for appropriate service orchestration solutions, since service users may need to integrate services from different providers in order to support their business processes (Papazoglou and van den Heuvel 2011).

When integrating services to higher-level functionalities, the associated workflow, i.e. the order of services to be integrated and, based on this, the kind of data to be exchanged among the services must be specified (cf. Mayer, Schroeder et al. 2008). To do so, the respective service input and output data must be linked and, if necessary, mapped. Figure 4.4 illustrates this for the above-mentioned example of an order execution service.

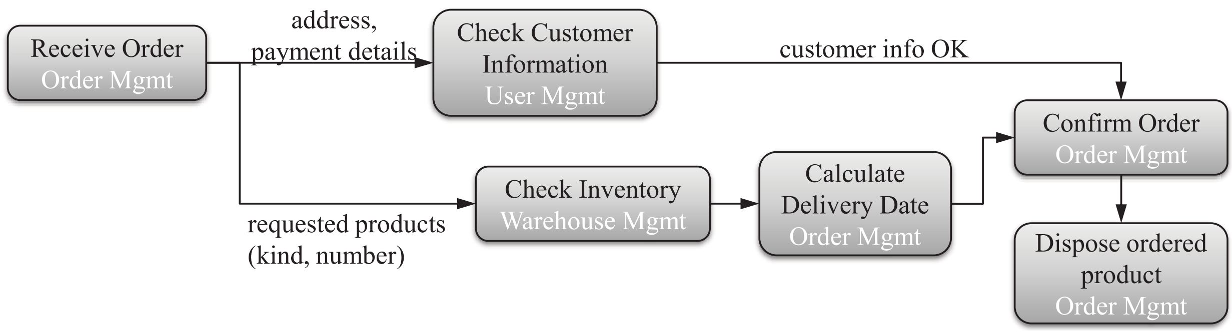

Figure 4.4. Sample workflow for an order execution service

Such workflows are usually created by means of modelling languages, primarily the Business Process Modelling Notation (BPMN), which is used to graphically define workflows, the Web Services Business Process Execution Language (WS-BPEL) and the XML Process Definition Language (XPDL), which are based on XML and focus on the configuration of executable business processes, as well as Yet Another Workflow Language (YAWL), which combines both approaches and comes along with an open source framework serving as workflow management and execution system. An alternative to executing workflows in respective systems based on these models is to configure them within the message routing functionality provided by ESBs (Hohpe and Woolf 2012, pp. 225–326).

The workflows resulting from such definitions can be executed automatically but are static. To configure workflows dynamically, i.e. to flexibly combine services on demand without know-how or significant manual configuration efforts, further-reaching support is necessary. This can be implemented e.g. by integrating ontologies to workflow configuration and execution systems in order to gain and utilise knowledge about services, their purpose, functionalities, and interfaces (Syu, Ma et al. 2012).

4.3.2. Configuration of Production Workflows

Similar to IT services, several production process steps must be configured and combined in order to manufacture complex, customer-specific end-products. A common approach to do so is the integration of product and production configurations as applied by (Ostgathe 2012, Bengel 2010). They describe models for representing pre-defined product variants and options, available production systems, process capabilities and associated configuration options, as well as relationships and conditions which define how production settings need to be adjusted in order to achieve specific product characteristics. Complementary, Pfrommer, Stogl et al. (2014) and Muckenhirn (2005) describe related information flows and IT systems which support configuration and execution of respective workflows.

To aggregate manufacturing processes and tasks automatically or across production sites, a common language, i.e. syntax and semantics, is required to describe production processes and tasks. This allows alternative processes to be compared and ensures that input and output definitions for the combined production processes are compatible with each other. Therefore, the extension of production workflow configuration and execution systems with ontologies as it is described by Syu, Ma et al. (2012) has to cover knowledge about process characteristics and classifications similar to the concepts explained in sections 4.1 and 4.2.

4.4. Knowledge Management

As mentioned in the previous section, knowledge-based systems can support the ad-hoc definition of production workflows throughout production networks. In doing so, they improve the efficiency and quality of workflow design by contributing to the automation of manufacturing service configuration and combination. This may include checking the manufacturability of products, i.e. the feasibility of the resulting product trees or process chains. To do this, the manufacturing service property models must be extended with respective constraints, thus enabling connections between services to be assessed by checking related rules.

4.4.1. Models for Product and Process Constraints

As explained in section 4.1.4, there are models for the customisation of manufacturing service properties, i.e. the parameterisation of geometric product descriptions and configuration of production processes and SLAs. However, this does not guarantee that customer-specific configurations of manufacturing services will not exceed the limits of production systems or processes. To take this into account, constraints – basically minimum or maximum values and pre-defined configuration options applicable to the properties of manufacturing processes and systems – are integrated into the respective models to make them available for feasibility checks (cf. Neumann 2015, pp. 63–68, Molcho, Zipori et al. 2008). In the same way, models used for product configuration describe limitations and pre-define available options for customisable products and their components (Hotz, Felfernig et al. 2014).

However, not only the restrictions of manufacturing service properties must be considered during product and production configuration, but also the potential impact of a specific parameter setting on other manufacturing service properties and limitations (refer to requirements **`Req09`**, **`Req14`**, and **`Req15`**). Consequently, knowledge-based configuration systems include dependency models to enable respective rules to be formulated and executed based on graphical or text-based description languages (Hotz, Felfernig et al. 2014, Yip, Corney et al. 2013).

4.4.2. Assessment of Connections between Manufacturing Services

Beyond this representation and validation of constraints, the completeness and correctness of connections between manufacturing services must be evaluated when analysing the manufacturability of manufacturing service combinations which form agile production networks. To do so, automated reasoning mechanisms can be utilised. For instance, Ameri and Patil (2012) and Giess, McMahon et al. (2009) apply inference rules to ontologies representing product, process, and equipment categories in order to identify and select appropriate manufacturing services for the integration into specific agile production networks. Given that the capabilities of manufacturing service combinations are determined, Lartigau, Xu et al. (2015) and Dotoli and Falagario (2012) prioritise manufacturing service combinations by considering QoS aspects, manufacturing service availability, and transportation times using bee colony or Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) algorithms in order to select the best alternative.

Product configurators, i.e. knowledge-based configuration systems, consider dependencies between products and their components with regard to quantities and properties. In doing so, many of these systems generate suggestions, customer instructions, and warnings by means of automated reasoning, which is applied to ontologies and rules formulating problem statements, conditions and restrictions (cf. Tiihonen, Felfernig et al. 2014, Shukor and Axinte 2009, Tseng, Chang et al. 2005).

However, these systems rely on pre-defined knowledge bases and rules and do not include their assessment and automated extension.

4.5. IT Solutions for Agile Production Networks

After describing relevant research for separate aspects of manufacturing service configuration and combination in the previous sections, the following gives an overview of methods and related IT tools which aim at providing holistic solutions for creating and managing agile production networks.

To share manufacturing services and implement agile production networks, a widely-used approach is to use web-based marketplaces, where service descriptions are published for consumers to find, select, and integrate them into agile production networks (cf. Ferreira, Sarraipa et al. 2014, Ameri and Patil 2012). These centralised indices provide information about and access to available resources via respective search and semantic match-making mechanisms and are a key component of virtual enterprise management or cloud manufacturing platforms, which aim at reducing the efforts involved in establishing, i.e. configuring and integrating, production networks.

Further aspects covered by these platforms include the configuration of supply chains and the execution of related manufacturing workflows. These can be implemented based on SoA principles, i.e. by integrating manufacturing resources in the form of modular and reusable service components. For instance, Schulte, Hoenisch et al. (2014), Wang and Xu (2013), Rauschecker, Stöhr et al. (2013) and Burghardt, Zimmermann et al. (2007) suggest to configure and manage agile production networks using centralised IT services to select and combine of manufacturing services, as well as to optimise and evaluate resulting production networks.

Besides this, there are also agent-based approaches, which focus on the distributed management and execution of workflows. Agent-based systems aim at executing tasks via multiple autonomous (software) agents, which pursue their individual tasks and objectives while interacting with an environment that may include further agents (Russell and Norvig 2014, pp. 34–62). In the manufacturing domain, this is implemented by representing items, basically manufacturing facilities or production jobs and related products, in the form of agents which optimise their utilisation or routes through production on their own (VDI/VDE 2653 Part 1 2010, Göhner and Weyrich 2014). Agent based systems can be used for managing agile production networks, for example with agents representing orders and related products which are routing themselves across production sites (Ameri and McArthur 2013, Rahman, Sadik et al. 2008, Ouzounis 2001).

4.6. Derived Research Gaps

The previous sections demonstrate that there are various solutions for the configuration of agile production networks, including the description and classification of manufacturing services, their combination to workflows, and related knowledge-based support. Table 4.2 gives an overview of these concepts and solutions and indicates to what extent they fulfil the requirements on the model and system as they were identified in chapter 3.

Requirement	Existing solutions	Fulfilment
`Req06`: Manufacturing service model	Product models such as STEP, IGES, or DXF	fulfilled
	Ontology-based production system and process descriptions (Negri, Fumagalli et al. 2016, Hoffmeister 2013, Konrad 2012, Loskyll, Schlick et al. 2011)	fulfilled
`Req07`: Parameterisation	STEP extensions (Pratt, Anderson et al. 2005), X3D applications (Yip, Corney et al. 2013)	fulfilled
	Variables and boundaries for production process settings (SiLA 2013, Konrad 2012, SEMI E139-0709)	fulfilled
`Req08`: SLA information	IT-Domain: WSLA (Keller and Ludwig 2003)	partial: concept transferable
	Non-IT service descriptions (Kiemes, Novelli et al. 2012)	partial: contents mostly text-based / not configurable

`Req09`: Dependencies between manufacturing service parameters	Integration of constraints and feasibility rules to configurable product models (Neumann 2015, Hotz, Felfernig et al. 2014, Yip, Corney et al. 2013)	partial: does not include integration with production systems
`Req10`: Level of detail for manufacturing services	Determined by granularity of respective models (ontologies, XML-based descriptions, etc.)	fulfilled
`Req11`: Online availability of manufacturing services	Provided by platforms for manufacturing service management (Schulte, Hoenisch et al. 2014, Rauschecker, Stöhr et al. 2013)	fulfilled
`Req12`: Common access point for manufacturing services	Manufacturing service marketplaces and indices (Ferreira, Sarraipa et al. 2014, Rauschecker, Stöhr et al. 2013, Ameri and Patil 2012)	fulfilled
`Req13`: Comparability of manufacturing services	Integration of manufacturing process categories into manufacturing service descriptions (Lu, Shao et al. 2014, Tao, Zhang et al. 2012, Giess, McMahon et al. 2009)	partial: within system boundaries

	Classification standards for industrial sectors, products, and manufacturing processes (NACE, ISIC, CPC, eCl@ss, DIN 8580:2003-09)	partial: not extendable
`Req14`: Definition of dependencies between manufacturing services	SoA-based workflow definitions (BPMN, WS-BPEL, XPDL, YAWL, ESB)	partial: integration of further knowledge about services required for automation; restricted to IT services
	Product-oriented production configuration (Ostgathe 2012, Bengel 2010)	partial: focus on parameterising single production systems
	IT-support for production workflow definition and execution (Pfrommer, Stogl et al. 2014, Muckenhirn 2005)	partial: focus on factory-internal product routing
`Req15`: Expression of dependency rules	Modelling of constraints in knowledge based configuration systems (Hotz, Felfernig et al. 2014, Shukor and Axinte 2009)	partial: focus on manufacturability in previously dedicated production systems
`Req16`: Separate, complementary model for dependencies	Rules referring to configurable parameters (Yip, Corney et al. 2013)	fulfilled
`Req17`: Gather knowledge from existing configurations and combinations	Extendable knowledge-based systems (Konrad 2012, Hitzler, Krötzsch et al. 2008)	fulfilled

`Req18`: Derivation of suggestions and feasibility validation for dependencies	Semantic discovery and match-making of manufacturing services (Ameri and Patil 2012, Cai, Zhang et al. 2011, Jang, Jeong et al. 2008)	partial: does not include the validation of completeness and feasibility of connections
`Req19`: Extensibility of the knowledge base	Ontologies and related meta-models (Hitzler, Krötzsch et al. 2008)	fulfilled

Table 4.2. List of model and system requirements and their fulfilment by existing solutions

From this comparison of requirements and existing solutions, it can be deduced that there is a need for further research, since a method, model and IT system covering all aspects to fulfil the requirements listed in section 3.6 could not be identified. Existing solutions either focus on the creation of static supply chains or are limited to fragments of agile production network configuration. For example, they only provide support for product modelling and manufacturability assessment based on static rules, without considering flexibly integrated manufacturing capabilities.

To develop an integrated approach, i.e. a method implemented by a model and IT system, for the configuration of agile production networks facilitating personalised production, the individual and intuitive configuration and combination of customisable manufacturing services needs to be addressed. To do so, research must be conducted with a focus on the following topics:

- A method for guiding manufacturing service providers and customers through the process of agile production network configuration by means of appropriate models and tools.

- An integrated, holistic manufacturing service model, which includes related parameterisation options and restrictions
- Representation of dependencies and constraints which apply to combinations of manufacturing services
- Manufacturability assessment of customer-specific manufacturing service configurations and combinations by means of validating completeness and correctness of dependencies

5. Defined Method

The strategies and methods for supply chain design and integration vary according to the industrial sector and company concerned. Therefore, this chapter describes a systematic approach to model, configure, and combine manufacturing services in order to align processes among participants in agile production network environments. This approach is made efficient by implementing models and utilising the related software system.

To ensure more fluent readability, the explanations in this and the two following chapters do not include the mapping of concepts and solutions, i.e. method, model, and IT system to the respective requirements gathered in chapter 3. However, this aspect is covered by the fulfilment assessment of requirements in chapter 8.

5.1. Overview

As described in sections 2.3.3 and 4.5, there are no standardised approaches for configuring and combining manufacturing services in order to support individualised production that go beyond the configuration of pre-defined options. Therefore, this method combines elements inspired by supply chain design, product configuration, and knowledge modelling, as they are described by Schönsleben (2011), Felfernig, Hotz et al. (2014), and Stuckenschmidt (2009).

As explained in chapter 3, different stakeholders are involved in setting up agile production networks. Accordingly, the developed method must consider the role-specific perspectives and activities of these stakeholders. As shown in figure 5.1, manufacturing companies are able to provide manufacturing services if they make respective strategic decisions and model and publish their manufacturing capabilities. Customers use the method and system to receive personalised products by defining their objectives, as well as selecting, configuring, and combining the respective manufacturing services. In doing so, the model and system contribute supporting features, particularly data management and dependency assessment, which rely on information gathered from previous agile production network configurations.

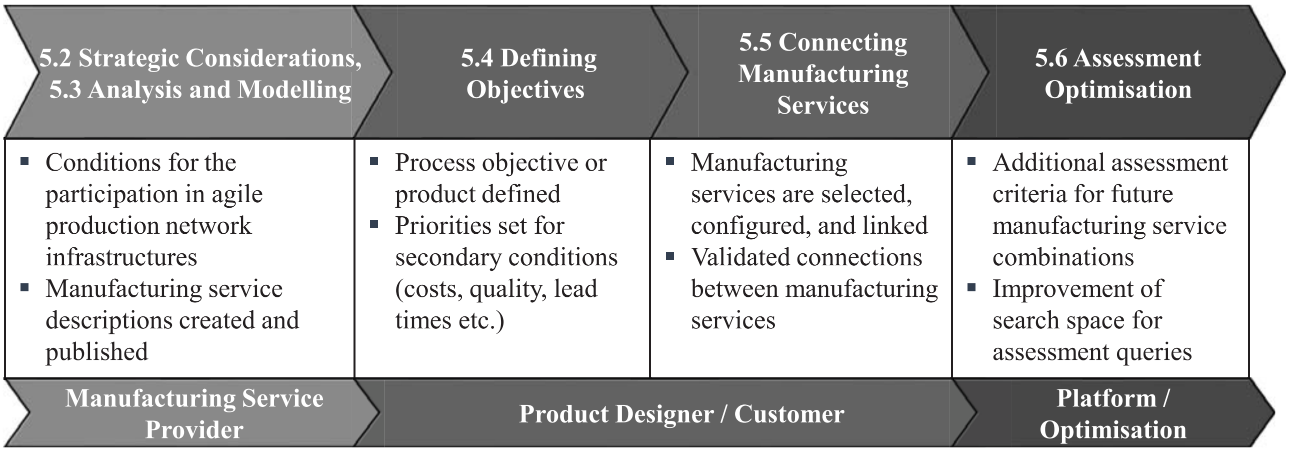

Figure 5.1. Overview of the stages of the method, their outcomes, and roles involved

The following sections describe the associated procedural steps in detail, including necessary considerations, decisions, and activities.

5.2. Strategic Considerations

The key requirement for configuring and combining manufacturing services to create and operate agile production networks is that manufacturing service providers want to share their capabilities and capacities. Their motivation to do so usually results from internal business strategies to improve market access or capacity utilisation. The proposed solution provides features which address the personalisation of product and process properties. These can be utilised directly by end-customers, thus contributing to the typical business objectives of manufacturing service providers.

After deciding to share manufacturing services in general, manufacturers need to define the products and processes, i.e. production capabilities and capacities, they want to offer for customer-specific configuration and integration into agile production networks. At the same time, they must determine the level of detail for the manufacturing services to be provided. Issues which need to be considered when making these decisions are:

- The confidentiality of certain product or process specifics of a manufacturing service, which must be upheld by excluding related parameters from manufacturing service specifications. If they are still needed, since related to process results provided to customers, these output parameters must be separated from those which define process input, e.g. in the form of machine program parameters. These confidential parameters and related calculations and conditionals may only be handled by company-internal systems and not be published.

- The granularity of available processes, which is defined by the production facilities used to execute them. For instance, in contrast to chained production lines, loosely coupled equipment allows processes to be split into their process steps, thus enabling these to be provided as separate manufacturing services.

- The degree of process flexibility, i.e. the ability to execute manufacturing processes with customised parameters without needing to spend major efforts on reconfiguring the production system (refer to section 2.3.1). The higher the flexibility of a production system, the more parameters can be provided for individual configuration by customers, and the larger are the sets of available values for those parameters.

- The degree of automation and IT integration of the manufacturer's production facilities, since this influences the efforts needed to execute customised processes. If the degree of automation and IT integration is low, process configurations usually require manual adjustment and execution, while a high degree of automation and IT integration allows automated processing of individually configured parameters. For both variants, the measures for adjusting process settings correspond with the overall process control methods in the manufacturing environment, and thus do not involve extensive additional work. However, media interruptions typically encountered in highly automated manufacturing processes with low IT integration cause increased efforts involved in executing customised process specifications (see also section 2.4.3).

- The complexity of the product or process to be provided by the manufacturing service, i.e. the extent of know-how required to customise it. Since customers usually do not have in-depth manufacturing knowledge about the products they buy, the manufacturing services must contain simplified specifics to render them suitably for as many customers as possible. This can be achieved, for example, by aggregating or substituting respective parameters to obtain characteristics which can be configured more intuitively.

5.3. Analysis and Modelling

After defining the products and processes to be provided in the form of manufacturing services, including their level of detail and related parameterisation options, these contents must be modelled and integrated into manufacturing service descriptions so that they can be published to the production network infrastructure.

To do so, manufacturing service providers must extract the relevant information from their production and IT systems, potentially aggregate or substitute parameters where necessary, and fill in a common description schema for manufacturing services in order to instantiate the data model for the specific product or process on offer. In doing so, contents for manufacturing service details which need to be comparable, i.e. product, process, and parameter categories, as well as parameter units, must be aligned across network participants. This is achieved by selecting them from a common repository provided by the agile production network infrastructure in the form of category trees.

When modelling manufacturing services and related input and output parameters, dependencies among these parameters need to be analysed. If any relationships between parameters exist, the respective dependencies expressing them must be formulated.

Furthermore, it must be verified whether certain conditions related to the application context of the manufacturing service apply, i.e. if the provided product or process requires the inclusion of previous or subsequent process steps on integration into a product tree or process chain at a later stage. If this is the case, respective application context conditions must be set by dependencies, which describe relationships between the categories of the products or processes provided by the manufacturing services to be connected.

To determine the dependencies to be included in the manufacturing service description, a guiding principle should be applied stating that only those rules which are really needed to ensure the feasibility of related processes must be modelled, since further rules would unnecessarily restrict customer options. These essential rules can be identified by applying a what-if analysis to the relationships in question, or to the categories or parameters affected by them. In particular, the relevance of rules can be determined similarly to the differentiation between alternative activity flows and exceptions in the context of a use case analysis (cf. Wazlawick 2014, pp. 64–74). In doing so, the impact of each relation is checked by evaluating the feasibility of the manufacturing service in case no rule is defined, and extremes selected for parameter values or categories, such as minimum, maximum, or far-fetched values. As a result, not only the required application context conditions are identified, but also parameter restrictions including affected parameters and their limits.

The result of this analysis and modelling step is the manufacturing service description, which includes details of product and process capabilities and related configuration options. This is then stored in a common manufacturing service index of the agile production network infrastructure, enabling it to be selected for integration into manufacturing service combinations. To keep the availability and related contractual details of the manufacturing service up-to-date without altering the overall product and process specification contents, the respective models are updated and managed separately.

5.4. Defining Objectives

Concrete manufacturing service configurations and combinations and thus related agile production networks are established based on a customer's or product designer's product idea. Accordingly, the main objective of the manufacturing service configuration and combination is to implement this product idea. However, to prepare its execution, the responsible customer or product designer has not only to define this product or process objective, but also to decide on further strategic objectives, i.e. costs, lead times, or quality, in order to prioritise manufacturing services with identical or similar outcomes, as well as to select the most appropriate alternative.

5.5. Connecting Manufacturing Services

After defining the manufacturing service capabilities to be utilised and prioritising further selection criteria, two different approaches can be taken to configure and combine manufacturing services:

- The preparation of a pre-defined template, which already includes the manufacturing services needed to implement a product of a certain type. These templates can either be prepared for this purpose only, or extracted from the data model by reusing previously specified manufacturing service configurations and combinations.
- Alternatively, customers or product designers can freely configure and combine manufacturing services from scratch, and use templates, if applicable,

only for sub-trees in their manufacturing service combination. However, depending on the complexity of the product, sound expertise in related production processes and components is required to configure and combine manufacturing services from scratch, while templates simplify this configuration and combination, thus addressing the needs of less skilled customers.

Whichever approach is used, specific manufacturing service combinations must be created either by adapting existing templates, or by selecting and integrating appropriate manufacturing services from the common repository. In doing so, manufacturing services must be compared with each other in order to ensure that the most suitable ones are integrated. This search and selection process can be supported by suggestions based on application context conditions, which recommend the inclusion of manufacturing services that belonging to a certain category or including a certain type of parameters. The selected manufacturing services are instantiated to prepare their parameterisation. Connections in the form of basic dependencies are established between these manufacturing service instances to represent the structure of the intended product tree or process chain.

In the next step, the parameters of the selected and combined manufacturing services are configured to address the specific needs of the customer's individually defined end-product. While setting respective values, it must be ensured that the output of a certain manufacturing service is compatible with the input of the one into which it should be integrated. This can be supported by an IT tool which compares and suggests parameter categories to be involved and checks the compatibility of parameter value ranges.

It may be the case that a manufacturing service combination is intended not only to be used to manufacture a particular customer-specific product, but also as template for other customers, e.g. if a product designer specifies a new product which can be further detailed by customers. If so, in addition to configuring related parameters, their restrictions and application context conditions relevant to connecting the selected manufacturing services must be defined. These relevant rules need to be selected and implemented in the same way as the ones applying to parameters within single manufacturing services (see section 5.3). Depending on the expertise of the product designer, this can also be supported by the recommendation of potential dependencies based on previously defined manufacturing service combinations, from which probable application context and parameter restriction endpoints are extracted.

Before executing an order implementing the specified product, the feasibility of the related manufacturing service configuration and combination must be verified, particularly if connections between manufacturing services were established which are not covered by recommendations, i.e. previously defined dependencies between related categories and parameters. To do so, as with generating recommendations for dependencies, reasoning mechanisms are used to generate warnings by inversing respective results. Additionally, the feasibility of parameter restrictions needs to be verified throughout the manufacturing service tree.

The recommendations and warnings provided by the system when creating and verifying of manufacturing service combinations are not strictly binding, since they indicate probabilities of respective dependencies. The accuracy of these probabilities depends on the quality and extent of the knowledge base that includes previously defined manufacturing service combinations and therefore does not cover every feasible option per se. Consequently, product designers and customers with sufficient expertise in related products and production processes are able to confirm newly established connections between manufacturing services which were not recommended, and for which warnings were generated.

Finally, after generating, verifying, and confirming the manufacturing service combination, its data model is used as basis for determining the respective order, which is then dispatched to the agile production network management, were it is further processed and executed.

5.6. Assessment Optimisation

Since the quality of application context and parameter restriction recommendations or warnings strongly depends on the number of pre-defined dependencies, newly created manufacturing service combinations are stored to a common platform repository. In this way, knowledge is gained about the included dependencies and potentially further detailed manufacturing service or parameter categories. This also goes hand-in-hand with other methods for defining ontologies, which follow an incremental approach and extend ontology contents in stages to iteratively improve them (cf. Stuckenschmidt 2009, pp. 162–164). As a result, the amount and extent of dependency and category models, and thus the size of the knowledge base for reasoning mechanisms used when configuring and combining manufacturing services, is extended incrementally during the application of the developed method and system. This storage process takes place automatically for all created manufacturing service combinations, thus maximising the knowledge base. To retain the confidentiality of individual manufacturing service configurations and combinations, they are not used as product type templates by default, but only queried for the purposes of validation and verification.

The described extension of the knowledge base and related re-use of previously defined dependencies results in improved reasoning results. These improvements are achieved in two ways. Firstly, the availability of additional dependencies for recommendations results in a larger amount of potentially recommended dependencies. Together with an increased granularity of the category model, it also leads to a more differentiated prioritisation of recommendations. Secondly, the reasoning mechanisms themselves can be improved by adjusting the number of iterations for including adjacent manufacturing service or parameter categories during the assessment of dependencies. This is because the number of iterations can be decreased as the number of already existing dependencies increases, resulting in smaller and thus less fuzzy solution spaces for potential dependency endpoints.

The optimised reasoning mechanisms are then available when further manufacturing service combinations are created, which are again stored and used for further incremental knowledge base extensions and assessment optimisations.

5.7. Summary of Procedural Steps

To provide a guideline for configuring agile production networks for individualised products, table 5.1 summarises the steps of the developed method which have been explained in detail beforehand.

Method stage	Procedural steps
Strategic considerations (manufacturer)	Business strategy decision to share manufacturing capabilities.
	Selection of the manufacturing service to be published, depending on the scope of the manufacturing company and strategic decisions.
	Definition of the level of detail and customisation options for the manufacturing service. These depend on the confidentiality of the respective product or process details, as well as on the complexity, granularity, flexibility, and degree of IT integration of the related production system.
Analysis and modelling (manufacturer)	Entering the specific manufacturing service contents, i.e. product and process properties, their customisation options and contractual details, into the pre-defined schema.
	Alignment of common terms, i.e. units and product, process, and parameter categories, with existing definitions provided by the platform's data models.
	Definition of necessary rules, i.e. application context conditions and parameter restrictions, which apply to the integration of the manufacturing service.
	Publication of the manufacturing service description on the platform to make it accessible by potential customers. This also includes regular updates of frequently changing manufacturing service information, especially the availability of related capacities.

Defining objectives (customer)	Definition of an individual product idea or process objective.
	Determination and prioritisation of other strategic objectives, in particular low costs, short lead times, or high quality.
Connecting manufacturing services (customer)	Selection of manufacturing services and/or pre-configured templates which contribute to the targeted product or process result.
	Receive recommendations for connecting manufacturing services based on manufacturing service categories and properties from previously defined dependencies.
	Linkage of manufacturing services, including the configuration of parameter values for the selected and linked manufacturing services.
	Optional inclusion of application context settings and parameter restrictions in the dependencies, thus preparing the configuration result for reuse, potentially supported by appropriate recommendations.
	Verification of configured parameter values, established dependencies, and related application context settings and parameter restrictions by means of reasoning mechanisms. These utilise previously defined dependencies of manufacturing service and parameter categories, and execute parameter restrictions with custom or limit values.
	Confirmation and order placement.
Assessment optimisation (IT platform)	Knowledge base extension by storing data models of newly defined manufacturing service configurations and combinations, particularly dependency details and potentially added category refinements.
	Detail assessment queries according to the rising number of dependency models and enhanced levels of detail of category models to make recommendations and warnings more precise.

Table 5.1. Summary of procedural steps

6. Model and System Conceptualisation

To prepare the implementation of the method and model for efficiently configuring agile production networks, which are tailored to individual customer requests, based on manufacturing services, this chapter describes the concept of the intended solution in the form of an IT system. The separate components of the solution are identified and drafted, taking into account their integration and interaction. The solution enables the creation and configuration of data models for manufacturing services and their dependencies to form agile production networks. It also allows them to be assessed, and related knowledge to be utilised and reused during the process of generating further manufacturing service combinations.

6.1. Structure of the Proposed Solution

The proposed solution consists of three major components, which are shown in figure 6.1: Information about manufacturing services to be shared, with related customisation options and constraints are represented by means of a principally static data model, i.e. manufacturing service description. This must be prepared by manufacturers and include all information needed to specify the technical, logistical, and economic aspects of the capabilities and capacities provided. In addition, dependencies must be modelled by service consumers who configure agile production networks for their personalised products by connecting manufacturing services, including the category-related and parameter-induced impact on them.

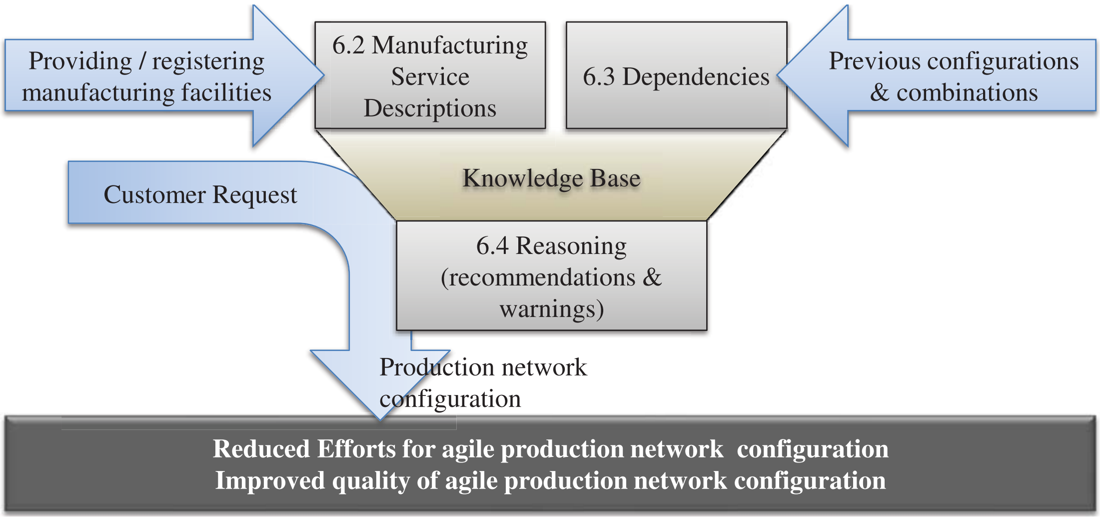

Figure 6.1. Solution approach for agile production network configuration

Both models are integrated to a knowledge base, which serves as index for manufacturing services and forms the basis for reasoning dependencies and their feasibility in order to provide recommendations and warnings aiding the configuration of agile production networks by non-experts. By means of these modelling and reasoning steps, the defined method is expected to reduce the effort involved in configuring agile production networks and improve the quality thereof (see also section 5).

6.2. Manufacturing Service Descriptions

The structure of the data model, which represents the properties and functionalities of manufacturing services, is derived from the intended scope, application, and alternative implementation options for manufacturing service descriptions as explained in the following.

6.2.1. Contents of the Data Model

The requirements indicate that the model for manufacturing services must describe all the information needed by production network partners or customers to use them. This includes general information required for administrative purposes, primarily details about the manufacturing service provider. However, the most relevant content of the descriptions is information about the input and output of the respective production processes. Therefore, the data to be included in the descriptions is identified based on the definition of production processes as product transformation, i.e. value adding processes (see figure 6.2). Customers request

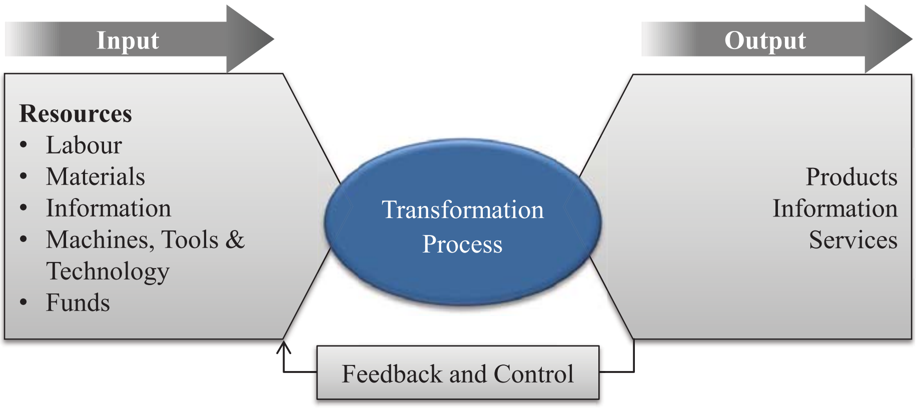

Figure 6.2. Product transformation by manufacturing services according to Slack, Chambers et al. (2010, pp. 11–14)

specific output from a manufacturing service, i.e. a process result or product, which is to be delivered in time and sufficient quality. To achieve this, related input for the transformation process must be supplied in the form of resources, i.e. raw material, machines and tools, labour, information, and funds. For personalised products, the representation of these input and output properties must reflect related conditions and restrictions to ensure that the customer-specific product definitions can be manufactured without exceeding limits given by machines, tools, or other involved resources. Consequently, the parameterisation of manufacturing service properties is integrated into their descriptions by including related options and restrictions. As customisable parameters are applied for various kinds of manufacturing service properties, manufacturing service descriptions need to include a generic parameterisation concept that can be integrated to each property as required.

In addition to specifying manufacturing service properties, the descriptions must be transferred to other production network participants. To do this, the descriptions are implemented as encapsulated, self-contained documents which include all necessary information and can be processed by different stakeholders who extract or edit the information they are interested in.

Based on these considerations, a generic manufacturing service description is drafted as visualised in figure 6.3, which also lists examples related contents in the context of Organic Light-Emitting Diode (OLED) production. This manufactur-

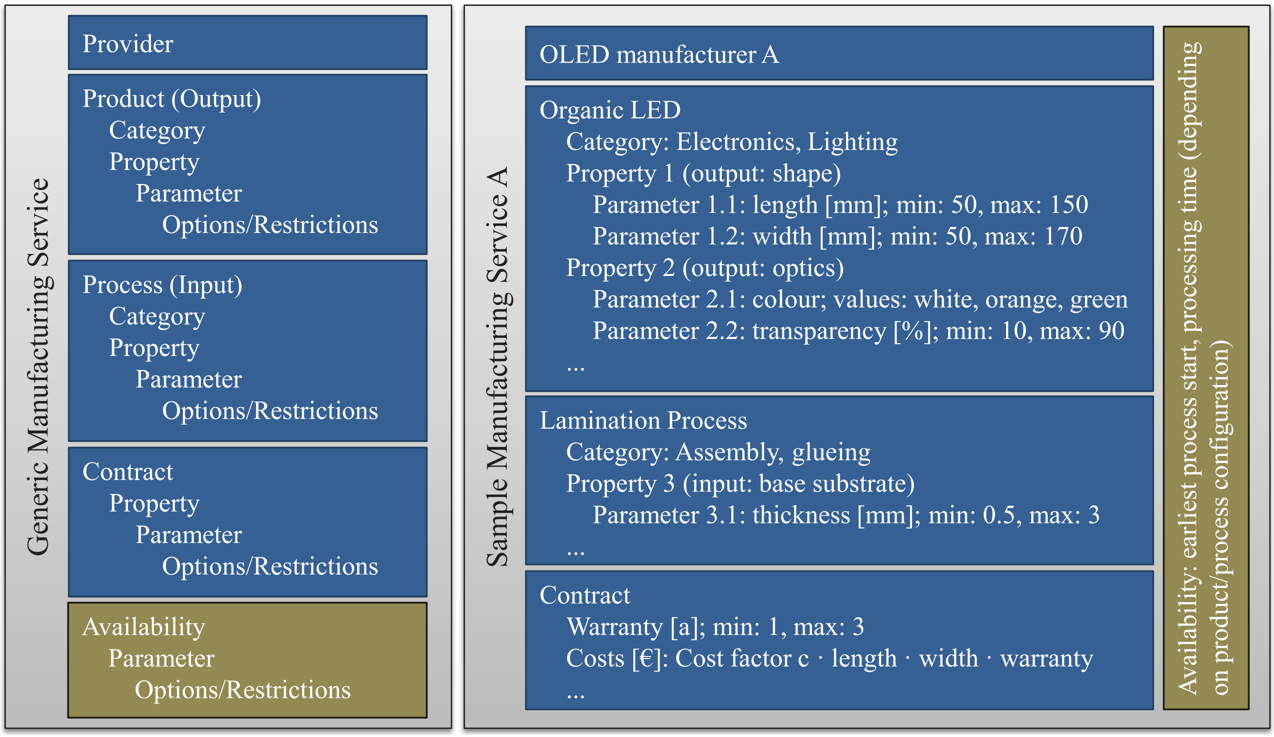

Figure 6.3. Contents of manufacturing service descriptions

ing service description represents a framework into which properties describing product, process, or contractual aspects of the manufacturing service are embedded. These properties are specified by means of parameters. If they can be adjusted to customer-specific needs, the parameter components reflect this by including related options and constraints. Additionally, product and process properties are assigned to respective categories in order to make them comparable across company boundaries. To address the need for frequent updates of the availability of manufacturing services, a separate component is integrated into the manufacturing service model, which can be updated and handled independently of other manufacturing service description contents.

6.2.2. Application Context of Manufacturing Service Descriptions

The usage of manufacturing service descriptions is shown in figure 6.4. Relevant contents must be extracted from factory-internal systems either manually or with the aid of (semi-)automated mapping mechanisms, depending on the capabilities of the respective factory IT systems. To select related product and process categories, guidance given by a centralised knowledge base providing standardised classifications ensures that these categories are appropriately interpreted and used.

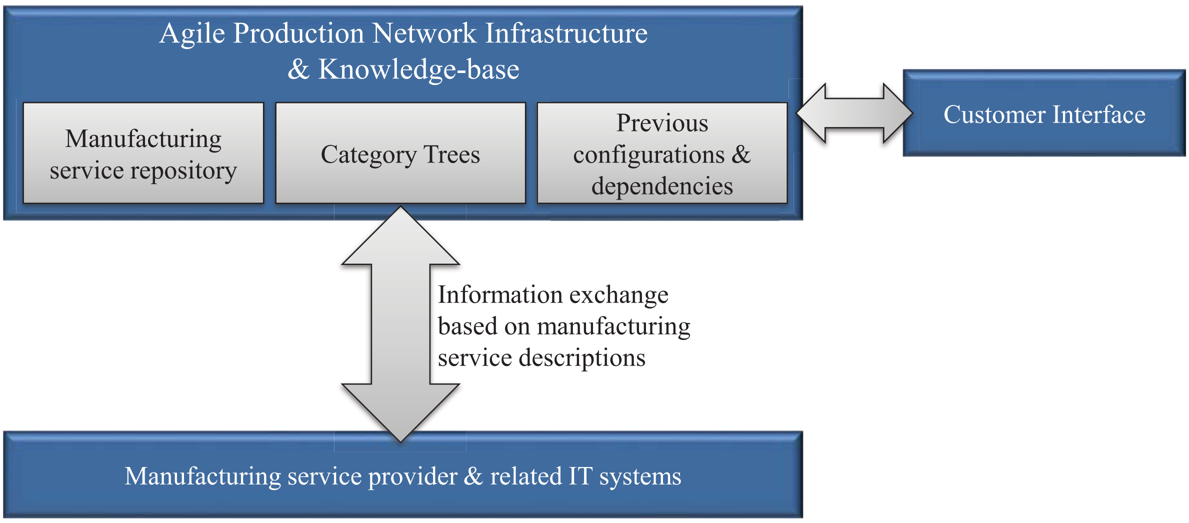

Figure 6.4. Exchange and processing context of manufacturing service descriptions

When manufacturing service descriptions are made available to potential customers, they are transferred to a repository in the agile production network infrastructure. From there, they can be selected for configuration and integration into specific agile production networks, i.e. customer-specific product trees or process chains. To do so, customers interact manually with the system, aided by automated information processing. Therefore, manufacturing service description contents need to be readable for both, humans and machines.

6.2.3. Approach for Implementing Manufacturing Service Descriptions

To enable information to be processed by humans and automatically, an XML based representation is widely applied. This also addresses the envisaged support of existing standards, since XML implementations exist for several relevant specifications such as B2MML, MyOpenFactory, or eCl@ss. Further advantages of XML representations can be extracted from the respective standards (Bray, Paoli et al. 2006, Fallside and Walmsley 2004):

- XML Schema Definitions (XSDs) allow manufacturing service descriptions to be validated regarding data types and completeness.

- Extensibility of XML schemas and related documents, which is achieved by means of namespaces and references to their elements. This enables multiple XML documents with complementary content to be linked. Furthermore, *any* elements support the inclusion of data elements which are not explicitly specified during the definition of XML schemas.

- The possibility to embed text and binary data in XML documents, enabling the integration of other data formats, such as those used for product descriptions.

Compared to XML, the JavaScript Object Notation (JSON) has equivalent advantages and is even faster to read and process (json.org 2006). However, many common standards do not support it yet, whereas XML became established longer ago. To overcome this issue and integrate these standards into JSON documents, transformation mechanisms as described by Boyer, Gao et al. (2011) can be applied. Consequently, JSON is regarded as suitable format for representing manufacturing service descriptions.

6.3. Representation of Dependencies

Equivalent to the approach for creating manufacturing service descriptions, concepts have also been developed for implementing dependencies between manufacturing services. These are described in the following.

6.3.1. Dependency Types and Contents

As explained in section 3.3, there are different kinds of dependencies between manufacturing services which need to be considered when configuring agile production networks. Furthermore, dependencies must reference manufacturing services without having an impact on the self-contained descriptions of these. Consequently, a separate representation of dependencies is developed containing information as shown in figure 6.5, which also gives an example of dependency contents in organic semiconductor processing.

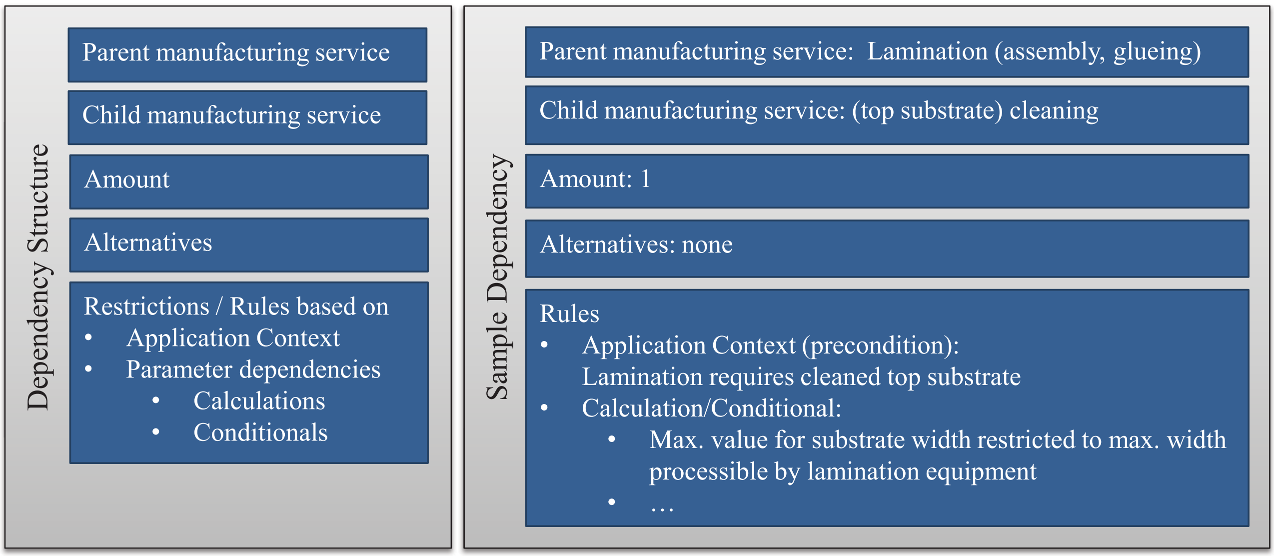

Figure 6.5. Contents of Dependencies

The structure of agile production networks is defined by means of dependencies which represent parent-child relationships between manufacturing services and include related quantities and alternatives. Therefore, dependency specifications include a child reference which points to the output of a specific manufacturing service, as well as a parent reference, i.e. the next manufacturing service in the product tree or process chain receiving input from the previous one.

To set the application context for each manufacturing service in the agile production network, the parent-child relationships must be extended with information concerning the required pre- and post-conditions for the manufacturing services to be connected. For instance, assembly processes require multiple components, tempering and finishing processes are usually executed before final assembly but after forming processes, and, in the semiconductor industry, lithography must be performed before applying etching or doping processes to wafers.

Furthermore, links between manufacturing service parameters and their contents need to be established to express the impact of specific parameter settings on other manufacturing service characteristics. For instance, the selection of a specific material, geometry, or surface characteristic may influence the range of customisation options for the other properties. This type of dependency occurs within single manufacturing services, as well as throughout product trees or process chains. The rules formulated to represent them must consider two types of logic relations between parameters:

- Calculations which either calculate output characteristics or update minimum or maximum values for available parameter ranges according to specific customer configurations. As an example, the size of an OLED lighting element frame is defined by the number n and outline of the involved OLED elements:

$$l_{frame} = n \cdot l_{OLEDelement} + (n-1) \cdot l_{OLEDdistance} + 2 \cdot l_{framenotch} \quad (6.1)$$

- Conditionals which represent dependencies that cannot be expressed by a stand-alone formula. This applies to all parameters that do not refer to a continuous range of values. For instance, the colour of an OLED can have discrete values, such as white, blue, green, or orange, for which different transparency options are available:

$$\begin{aligned}((colour = (\text{“green”} \vee \text{“blue”})) \rightarrow (transparency \leq 10\%))\\ \wedge((colour \neq (\text{“green”} \vee \text{“blue”})) \rightarrow (transparency \leq 45\%))\end{aligned} \tag{6.2}$$

Also a combination of both, calculations and conditionals, may be necessary to model parameter dependencies if discrete outcomes resulting from conditionals are used to calculate further parameters. An example for this is the power consumption P_{oled} of an OLED lighting element which depends on its Area A_{oled}, and its colour:

$$\begin{aligned}((colour = (\text{“white”} \vee \text{“blue”})) \rightarrow (P_{oled} = \frac{A_{oled} \cdot 2.308}{100} \frac{W}{cm^2}))\\ \wedge((colour = (\text{“green”} \vee \text{“orange”})) \rightarrow (P_{oled} = \frac{A_{oled} \cdot 1.846}{100} \frac{W}{cm^2}))\end{aligned} \tag{6.3}$$

6.3.2. Approach for Implementing Dependencies

In addition to the criteria applying to the selection of a technology to describe manufacturing services (see section 6.2.3), it must be considered that different kinds of rules need to be implemented when modelling dependencies: category based application context settings, and calculations and restrictions of parameter values.

There are different options for modelling the application context of manufacturing services by connecting their categories. The relationships between manufacturing service categories could be represented by mapping tables as they are used in relational data models. However, when considering the application of such models for validation and reasoning purposes, related queries become complex and time consuming because they must be assembled from various partial queries which request information about a manufacturing service, its category, relationships with which this category is involved, categories contributing to these relationships, and manufacturing services assigned to these categories. Graph-based data models and data bases overcome these issues since they focus on representing ontologies and relationships between entities by describing objects (nodes) and their relationships to one another (edges) (Angles 2012). Therefore, they can represent relationships between manufacturing service categories directly without workarounds such as mapping tables, which results in queries being processed faster. Additionally, the representation of bidirectionally ramified category trees, which need to be established to classify and compare manufacturing services, can also be implemented by means of related graph structures.

To represent calculation and restriction rules, there are various rule languages and interpreters. For instance, Semantic Web Rule Language (SWRL) enables rules to be integrated into OWL ontologies (O'Connor, Knublauch et al. 2005), and Rule Markup Language (RuleML) combines standards which model rules or data transformations, such as Production Rule Representation (PRR), SWRL and Extensible Stylesheet Language Transformations (XSLT) (Boley, Paschke et al. 2016). Furthermore, various proprietary rule and workflow engines, such as Drools, Jess, and Jena, provide specific languages which, although generally providing a wider range of features for representing rules, do not express them in a standardised format.

These rule languages and related interpreters mainly focus on inferences from existing ontologies, or on the definition and execution of workflows. When trying to combine this with the expression of calculations and conditionals, the complexity of rule expressions increases disproportionately to the number of parameters and conditions which need to be considered. This makes them unsuitable for use by manufacturing service providers, product designers, and customers who are usually not familiar with the coding of complex expressions.

Besides this, calculations and conditionals must uniquely reference the parameters which they connect. This means that it is not sufficient to include references to general parameters. Instead, the rules must point to unique parameter instances and values within specific manufacturing service configurations. However, rule languages and engines often define generic rules which are applied for all instances of a class or object type, or which react to pre-defined events. None of these variants fulfils the requirements for representing calculations and conditionals.

By contrast, these requirements can both be fulfilled by applying spreadsheets. They also address the need for usability, since most manufacturing service providers, product designers, and customers are used to respective tools. Appropriately configured tables enable variables to be inserted into cells by means of interfaces to other IT systems, which are integrated via a Real-Time Data (RTD) server. If these variables represent references to specific manufacturing service parameters and their values, these references can then be used in further formulas and conditionals or combinations thereof, which are described by standard spreadsheet expressions. The results of these formulas, i.e. cells where the results are located, can again be linked to the IT system by means of references which point in the opposite direction and write back the resulting values to manufacturing service parameters and their restrictions.

From these considerations it can be deduced that it is not productive to implement dependencies using one of these technologies but rather to combine semantic technologies and spreadsheets. Java classes and related interfaces can serve as backbone for modelling manufacturing services and their dependencies because they are able to represent the structure and contents of the JSON representations of manufacturing service descriptions, as well as to integrate interfaces to graph-based models and RTD servers, i.e. spreadsheets, as illustrated in figure 6.6.

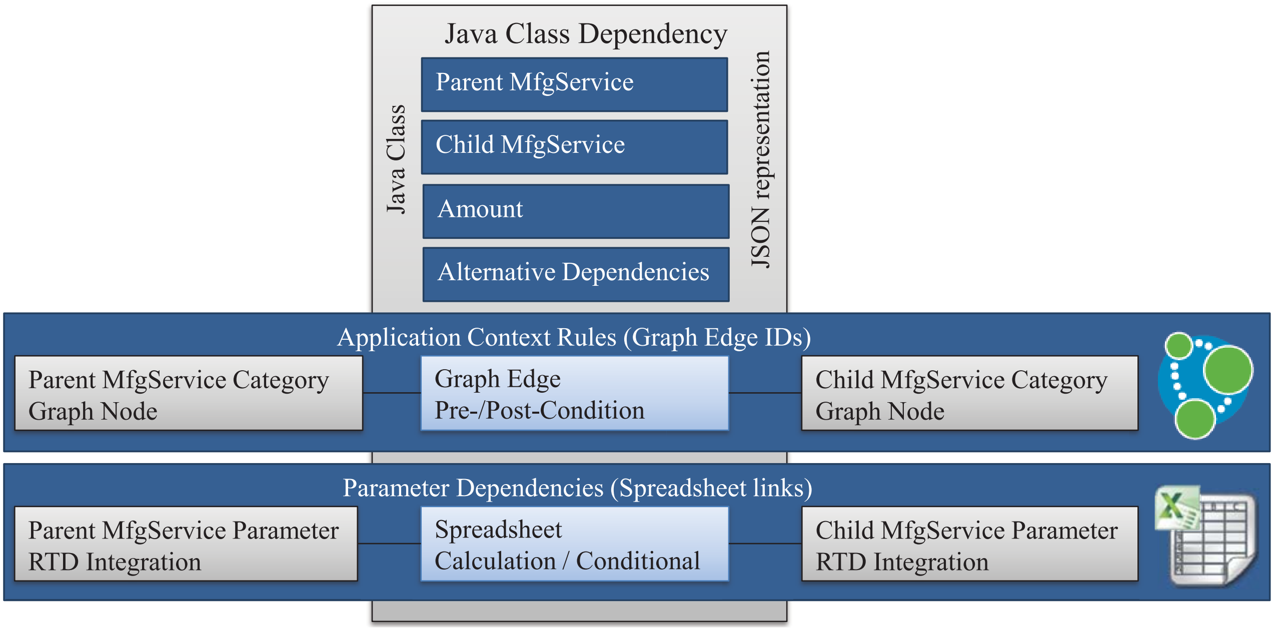

Figure 6.6. Technology stack for dependency models

6.4. Reasoning of Dependencies

To assist customers with combining manufacturing services, i.e. to provide recommendations and warnings when establishing dependencies, it is essential to assess the feasibility of the intended relationships between the respective manufacturing services. To do so, the potential restrictions and requirements of these relationships must be analysed in order to ensure the completeness and correctness of dependencies and resulting manufacturing service combinations. This can be achieved by taking into account previously defined dependencies between manufacturing services, which enables knowledge about practicable combinations and rules to be derived.

6.4.1. Objectives and Required Information

The assessment of the feasibility of manufacturing service configurations and combinations, i.e. the related dependency reasoning, can be split into different aspects: support with establishing the application context of a specific manufacturing service, assessment of the validity and correctness of parameter restrictions configured by the customer, and the recommendation of potentially lacking parameter restrictions to simplify and accelerate the overall configuration procedure.

Establishing the Application Context

As mentioned in section 6.3.1, the application context of manufacturing services can be defined via dependencies between their product and process categories. Related statements like *"OLED Lamination requires an OLED substrate and a cleaned top substrate"* can be used to check the correctness and completeness of manufacturing service combinations which involve processes or products of the same category.

To do this, inferences are derived from existing dependencies, as shown in figure 6.7. In this example, a manufacturing service X from category A has been linked

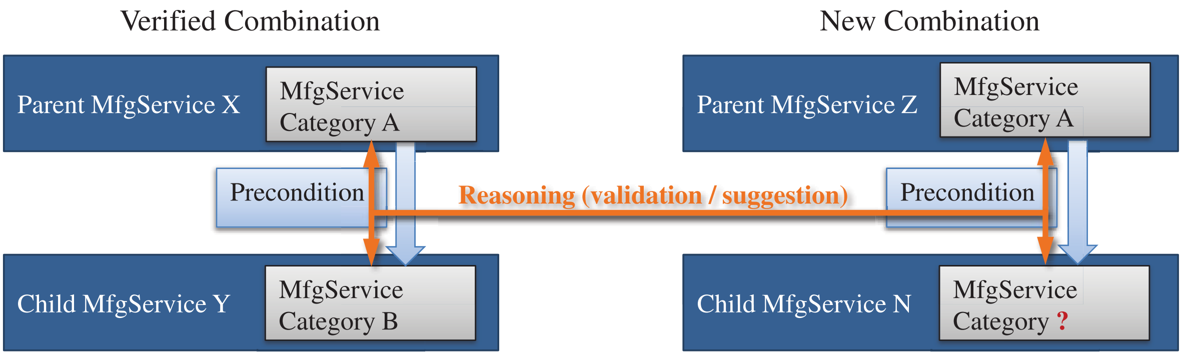

Figure 6.7. Exploitation of application context knowledge

to a preceding process (manufacturing service Y from category B). Based on this information existing in the knowledge base, a new manufacturing service combination involving a manufacturing service Z, which also belongs to category A, is checked against the same precondition which leads to a recommendation for connecting a process from category B. In doing so, the ramified structure of categories must be considered, thus allowing these rules to be specified independently of the level of detail of a specific manufacturing service's category.

For the OLED lamination process example mentioned above this means that a newly defined manufacturing service combination is identified as potentially incorrect or incomplete if the connected manufacturing service also includes a lamination process but links it with a top substrate component which is coated instead of cleaned. At the same time, carbon dioxide snow cleaning or a wet chemical etching process, which both belong to cleaning subcategories, would be identified and recommended for a potentially required or reasonable connection.

The ability of manufacturing services of similar categories to be replaced by one another increases with the degree of overlap of their typical properties. Thus, this reasoning can be refined, and related assessment results improved, by considering the types of properties which are assigned to manufacturing services of a specific category.

Verification of Parameter Restrictions

In addition to establishing and assessing the application context of manufacturing services in order to verify the endpoints of dependencies, i.e. connections between manufacturing services, the verification of linked parameters and related restrictions focuses on the contents of these dependencies. It ensures that the parameter values of involved manufacturing services do not exceed the limits set by their value ranges or available discrete values. The verification applies to the settings of all manufacturing services integrated into a specific product tree or process chain. Consequently, the impact of customer-specific end-product characteristics on all manufacturing services providing input into the end-product must be verified. This can be realised by reversely and incrementally executing the calculations and conditionals defining dependencies between the input and output parameters of manufacturing services as shown in figure 6.8, which illustrates an example of one iteration.

First, it is verified whether the specified end-product (result of manufacturing service X) is achievable within the limits of the respective input parameters, and the specific values of these input parameters are set to meet the output specification by reversely executing related calculations or conditionals. Then, these input parameters are mapped with the output parameters of the contributing manufacturing service A by solving the related dependency rules. Again, the required

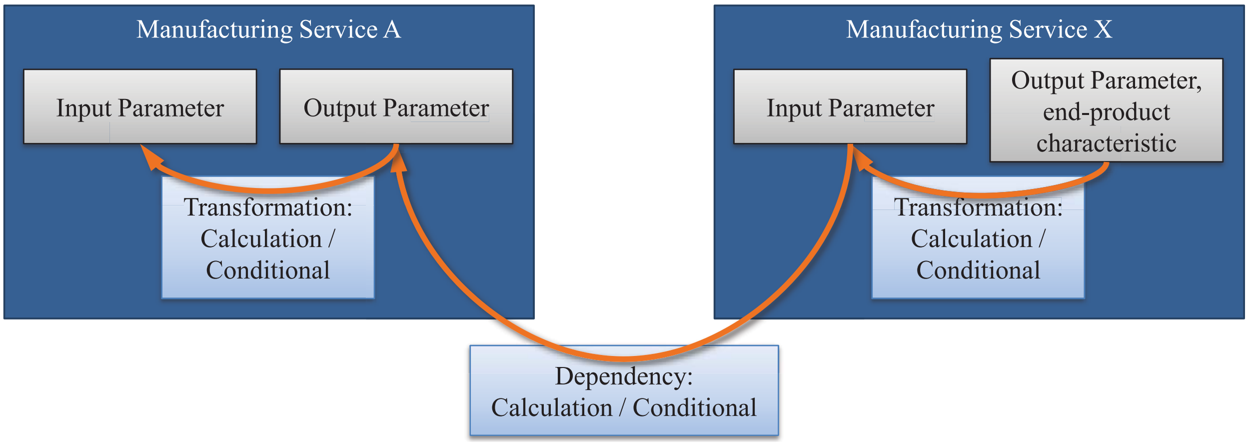

Figure 6.8. Verifying manufacturability through reverse parameter resolution

input parameters for that manufacturing service A are calculated to achieve the required output while considering related limits, etc. As a result, warnings are generated for customer configurations requiring invalid parameter settings for any manufacturing service involved.

However, this approach only provides a solution for the verification of existing dependencies between manufacturing service parameters. Additional inferences are necessary to assess completeness and recommend dependencies.

Recommendation of Parameter Restrictions

Inferences which verify or recommend dependencies between parameters can be realised by considering related parameter categories, similar to the usage of manufacturing service categories for establishing application context. The example in figure 6.9 illustrates this concept: Dependencies are established between specific manufacturing service parameters in the form of calculations and conditionals. If manufacturing services of the same category, or manufacturing services described by the same property types, are combined at a later stage, the calculations and conditionals to be configured should point to parameters of the same types.

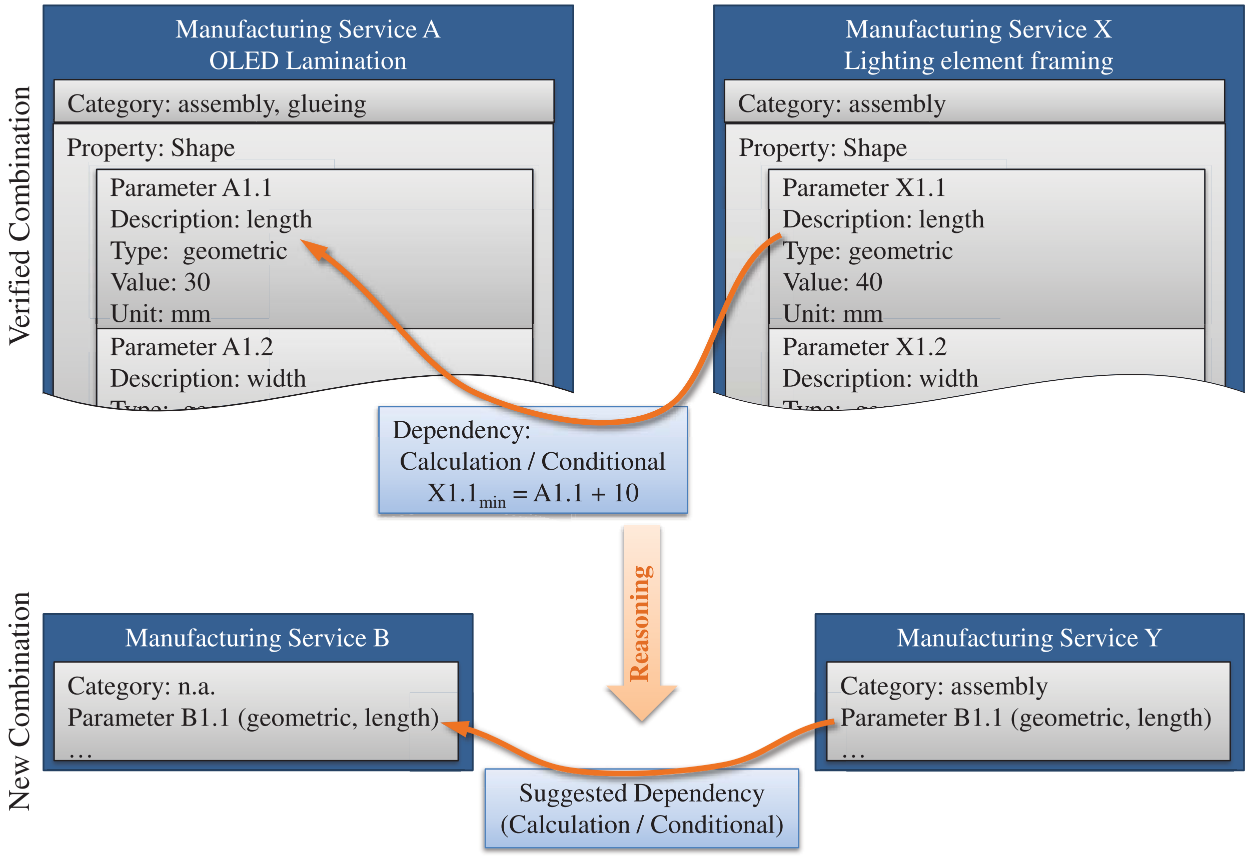

Figure 6.9. Extrapolation of relationships between parameters

To achieve this, not only must the generic relationships between manufacturing service categories be modelled, but also the properties of manufacturing services be categorised and relationships between them set up. In other words, the knowledge base and inference mechanisms used for representing, storing, and reasoning the application context of manufacturing service combinations must be extended by appropriate models and rules for representing and determining relationships between associated parameter categories.

6.4.2. Approach for Implementing Dependency Reasoning

To implement dependency reasoning concepts as they are described above, the applicability of several AI methods has been evaluated. In doing so, key criteria were extracted from requirements and concepts drafted and mapped against the features of some common AI methods described by Russell and Norvig (2014), Karaboga, Gorkemli et al. (2014), and Delen and Sharda (2008). Table 6.1 shows an overview of the results of this evaluation.

Criterion \ AI method	Semantic Networks	Neural Networks	Genetic Algorithms	Bayesian Networks	Fuzzy Logic	Artificial Bee Colony / Swarm Intelligence
Handling discrete, structured data	X	X	X	X	X	X
Search in manufacturing category and dependency graphs	X	-	-	-	-	-
Consideration of multiple constraints	X	X	X	X	-	-
History-based calculation of priorities / probabilities	-	X	-	X	X	X
Extensibility / learning mechanisms	X	X	-	-	-	X

Table 6.1. Overview of relevant AI methods

As it can be seen there, none of these AI methods addresses all the requirements on the intended solution. Therefore, a combination of a semantic network with conceptual ideas from artificial neural network and bee colony approaches has been selected. This enables graph search and prioritisation of search results based on previously gathered samples, which are both suitable for considering multiple criteria. In detail, this means that a semantic network is used to represent the knowledge about manufacturing services and related dependencies, and to derive suggestions for dependencies based on inferences regarding categories. The priorities of recommended dependencies derived from the knowledge base are calculated from the number of previously established links between manufacturing services equivalently to the weights of connections between different neurons in neural networks. Furthermore, priorities are derived from manufacturing service and parameter categories and adjacent positions in the category tree in a similar way as potential additional targets are selected in the artificial bee colony algorithm.

Besides the functionalities provided by reasoning mechanisms, the approach to implement the representation of dependencies has been considered when selecting technologies for implementing this dependency reasoning concept. Since dependencies related to the application context of manufacturing services are represented by graph-based models, the reasoning mechanisms for assessing such dependencies must be able to query these models, and to derive information about the feasibility of respective manufacturing service combinations from them. This can be achieved by applying inference rules which can be expressed by languages such as SPARQL and SWRL, or equivalent proprietary query languages of graph-based databases. Neo4j, a graph-based database which also is compatible with RDF ontologies, provides the ability to process both: its native query language Cypher and SPARQL inference rules (Neo Technology Inc. 2016, Hoyer 2014). Depending on the need for standard compatibility or performance, inference rules can be expressed and applied by using one of these languages respectively.

For establishing application context, related queries must comprise complex relationships which include multiple nodes of the graph-based models, i.e. parameter and manufacturing service instances and related categories. Furthermore, these inference rules can be used to implement reasoning of recommendations and potential restrictions for dependencies between parameters. However, respective rules are not restricted to connections between categories, i.e. nodes of a particular type, but need to consider parameter categories in the context of the manufacturing service to which they are assigned, as well as the related product or process category.

Such graph-based reasoning mechanisms, which handle complex and spanned dependencies, can also be applied throughout multiple manufacturing services or even whole product trees or process chains. For instance, etching processes may affect or even eliminate results from previous semiconductor processes, such as deposited layers and structures, and not only on the result of the immediately preceding process.

To ensure that these relationships between multiple manufacturing services are not only feasible regarding product, process, and parameter categories, but also regarding specific product and process settings in the form of parameter values, the assessment of associated dependencies must also include the verification of restrictions of parameter values throughout a series of dependencies. Since the related calculations and conditionals are represented by spreadsheets, their correctness can be checked by setting the input parameters of the spreadsheets to their respective maximum or minimum values, and comparing the resulting outputs with the limits of the input parameter restrictions for the subsequent manufacturing service. This is done throughout the whole tree of dependencies by iteratively testing each dependency rule.

Besides identifying appropriate manufacturing services and parameters to be connected, customer decisions for configuring and combining manufacturing services are supported by prioritisation of potential connections. To do so, the similarity of previously established dependencies is analysed regarding the manufacturing services linked and their input and output. In this context, similarity is defined as the degree to which dependencies overlap with regard to related manufacturing service categories and parameter types. Furthermore, the number of similar, i.e. probably matching dependencies already in existence, is considered when prioritising dependency recommendations.

When reasoning dependencies, it does not make sense to verify all dependency aspects simultaneously because this, for example, would waste time and effort involved in reviewing and proposing parameter restrictions for combinations of manufacturing services with incompatible categories. Therefore, dependency reasoning is executed according to the level of detail of the related dependency information, as shown in figure 6.10.

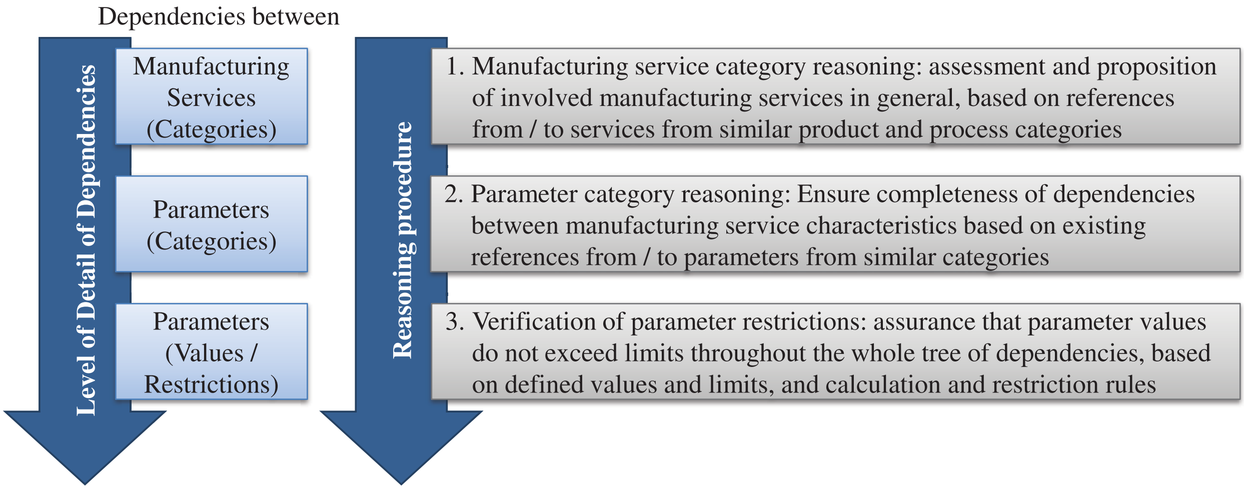

Figure 6.10. Reasoning sequence for dependency assessment and recommendation

6.5. Concept Summary

The previous sections define models and system functionalities supporting the configuration and combination of manufacturing services to implement agile production networks. In doing so, three major pillars for establishing, recommending and assessing dependencies between manufacturing services have been identified:

- Manufacturing service descriptions, which represent information about manufacturing services and their properties in a standardised format.
- Dependency models, which contain information about existing links between manufacturing services regarding their application context, as well as their associated parameters, values, and restrictions.
- Reasoning mechanisms, which utilise the knowledge base containing information about existing manufacturing services and dependencies in order to derive recommendations and feasibility statements for newly established manufacturing service combinations. This is achieved in three steps, according to the level of detail or concerned dependencies: Establishing the application context of combined manufacturing services by means of product or process categories, identifying potential relationships between parameters and

their restrictions based on parameter categories, and verifying relationships between parameters by considering selectable parameter values.

These system components are implemented using semantic models which represent manufacturing services and their dependencies, as well as semantic rules, calculations and conditionals which are applied during reasoning. The next chapter describes this implementation, as well as the integration of respective system components.

7. Design and Implementation

This chapter describes the implementation of the concepts for models and related reasoning mechanisms specified in chapter 6. First, the realisation of manufacturing services is explained. Then, the representation of the various types of dependencies between them and related queries are detailed in bundles according to the reasoning steps for assessing the manufacturing service combinations they contribute to. In doing so, the structure and contents of the models, assessment queries, and their integration are described generically before explaining how they are implemented in a software system by means of specific technologies.

The models of agile production networks, i.e. manufacturing services and dependencies, are designed using Unified Modelling Language (UML) class diagrams. The key elements of this notation are shown in figure 7.1.

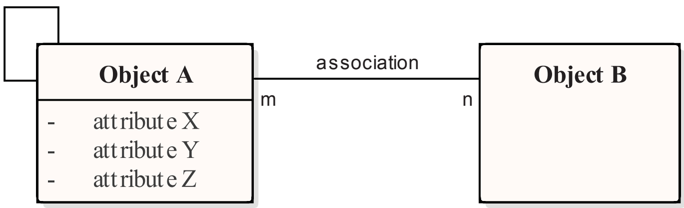

Figure 7.1. Relevant UML notation elements (Wazlawick 2014, pp. 113–132)

Generic objects are represented in the form of classes like *Object A* and *B*. Classes representing the context of this work are, for example, *ManufacturingService*, *ManufacturingServiceCategory*, or *Parameter*. Each class contains attributes (e.g. *X*, *Y*, and *Z*) which specify characteristics of the related object by means of predefined data types. These data elements can be unique identifiers, names and descriptions, or any other specific information. Classes may be linked to one another via associations which define that *Object B* belongs to *Object A*, as is the case for a product or process category to which a specific manufacturing service is assigned. An object (A) can also reference itself, for instance categories in a tree structure with children that are also categories. For these links, related quantities are indicated by the variables m and n, which define that *Object A* refers to n instances of *Object B*, and each instance of *Object B* can contribute to m instances of *Object A*. In doing so, typical values and ranges for these variables are *0..** for any quantity, *1* if exactly one object is assigned via the association, or *1..** if a minimum of one object is included.

7.1. Manufacturing Services and their Customisation Options

This section specifies the structure and implementation of the data model for manufacturing services in order to cover all aspects relevant to configuring agile production networks. The model structure defined in section 6.2.1 is refined, implemented by means of a standardised format (see section 6.2.3), and supplied to the overall software system for supporting agile production network configuration as a basic component referenced by dependency and reasoning solutions.

7.1.1. Contents and Structure of Manufacturing Service Descriptions

As outlined in section 6.2, manufacturing service descriptions contain information about providers, product or process categories, their characteristics and related parameters, as well as contractual aspects. They are implemented in the form of an independent model document to ensure that each manufacturing service can be integrated to multiple agile production networks.

There are two ways of integrating relevant information to manufacturing service descriptions: Contents which are only assigned to one specific manufacturing service can be inserted directly into the descriptions in the form of *inclusions*, i.e. attributes which cannot be reused in other object instances. Accordingly, information which can be associated with more than one specific manufacturing service must be integrated to manufacturing service descriptions as *references*. This also simplifies the management of contents as it avoids redundancies and corresponds with the concept of clustering information in classes according to their logical affiliation. Therefore, the latter is chosen as key concept for integrating information to manufacturing service descriptions. Figure 7.2 shows the resulting class diagram for manufacturing service models.

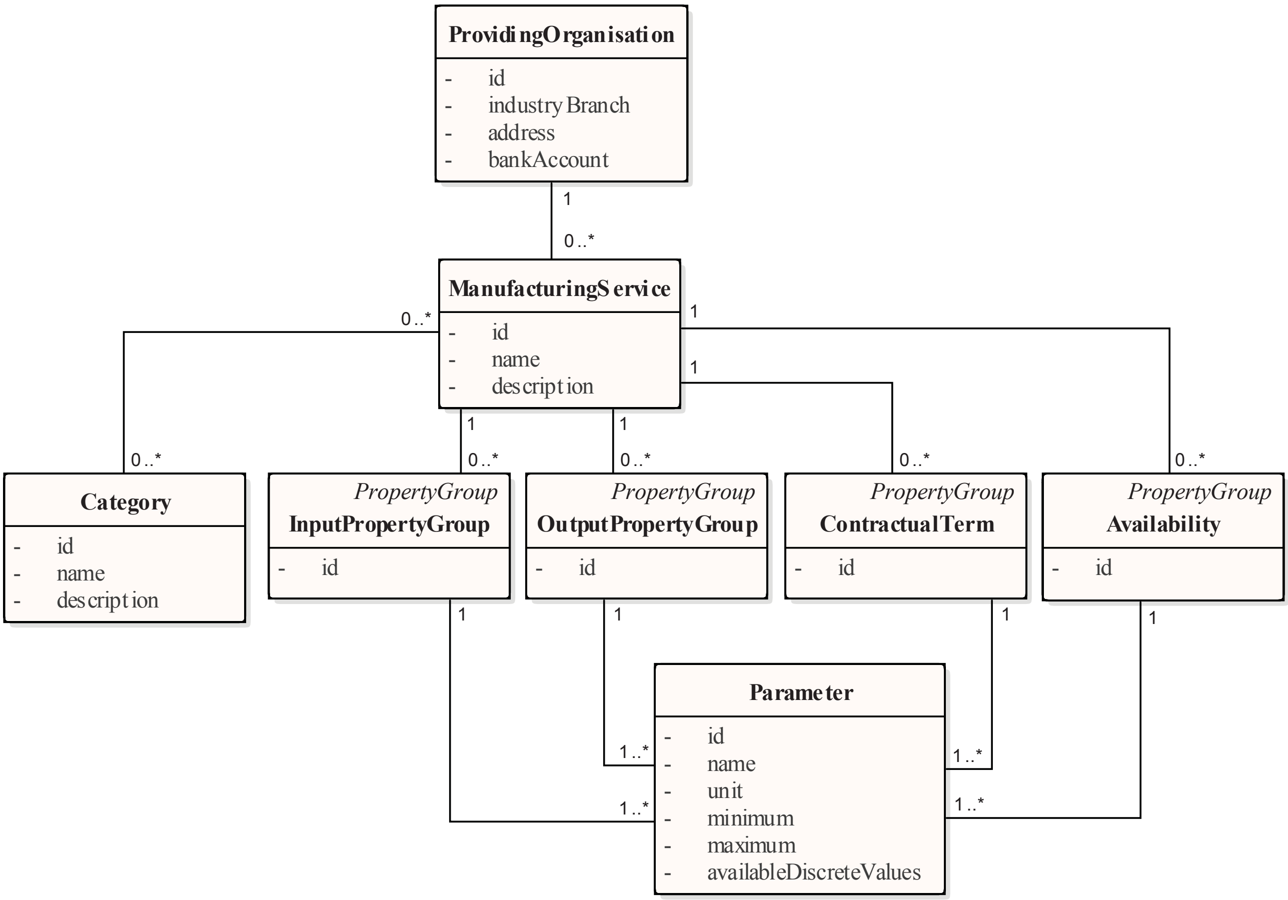

Figure 7.2. Data model of manufacturing service descriptions

To use manufacturing services and their descriptions in agile production network infrastructures, information about the **providing organisations**, including company address, bank account details, and industry sector need to be shared. This enables requests and orders to be dispatched to providers in order to implement customer-specific configurations. In this context, it must be considered that a manufacturer may provide multiple manufacturing services, but that each specific manufacturing service only has one provider.

When classifying manufacturing services, it is essential to considered that a manufacturing service can potentially be assigned to several product or process **categories**. For example, lamps are classified by eCl@ss as category 27 “electrical, automation, and process control technologies”, but desk lamps could also be grouped into the category “office equipment” and may be the result of an “assembly” process at the same time. Vice versa, each product or process category can be implemented by multiple manufacturing services.

All properties of a manufacturing service, e.g. for an organic semiconductor process as shown in figure 6.3, must be related either to its input or output. Typically, **input properties** describe process parameters and raw materials, while **output properties** specify the resulting product. The detailed description of manufacturing service characteristics is implemented using **parameters** to determine their values. Parameters must be able to include any data type – from simple figures and terms like the length and colour of a process result, through to the complex objects as they are needed to integrate CAD models. This is implemented by including generic objects and byte arrays, which allow any figure, text, reference to another class instance, or files to be integrated.

To support the customisation of manufacturing services, their configuration options, i.e. details of adjustable input and output properties, need to be integrated into the representation of parameters. In doing so, available parameter values are defined by applicable boundaries of parameter ranges which are indicated by related **minimum** and **maximum** values, and by sets of **selectable discrete parameter values**. If dependencies exist between the parameters of a manufacturing service, the calculations and conditionals to express them are integrated into respective dependency classes including references to concerned parameters, as illustrated in figure 7.3.

Due its generic structure and data elements, this parameter and dependency model can be used to represent different kinds of manufacturing service para-

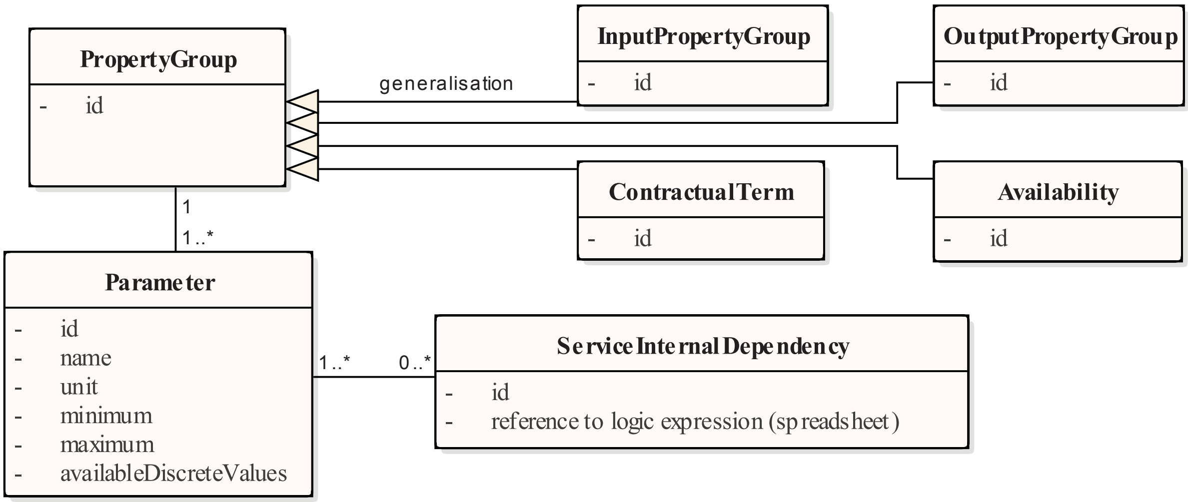

Figure 7.3. Parameter and dependency model

meters: characteristics which are selected by customers like the appearance of a product, those resulting from customer configurations like the energy consumption of a resulting product or required input materials for the process, as well as tolerances specifying the quality of a process result which may depend on other configurable parameters.

The quality of process results is a key element of SLAs. Related parameters are clustered together with other details about properties, such as guarantees and costs, thus representing the **contractual details** of a manufacturing service. Each of these characteristics is modelled in the form of parameters. Accordingly, the contractual details of a manufacturing service can be regarded as a special group of properties to which these parameters are assigned.

Information about the **availability** of manufacturing services, which must be shared throughout the production network in order to align and balance lead times and capacity utilisation among contributing participants, also can be integrated to manufacturing service descriptions via references. This enables information about the availability of a manufacturing service, primarily process set-up and lead times, capacities, current utilisation, or already confirmed production jobs and capacities which are reserved to fulfil them, to be updated without editing entire manufacturing service descriptions.

To ensure that the data model conforms to existing standards that already provide lean data structures for certain information, the contents and structure of classes containing information which is already modelled by these standards have been aligned respectively. For instance, information about manufacturers, including their contact details, address or bank account, are implemented according to the myOpenFactory standard (myOpenFactory Software GmbH 2009), which also defines a data structure for product classifications. The WSLA specification provides a model for representing SLA parameters, which are specified by name, unit, and data type attributes, similar to the *Parameter* object described above. However, both standards have been developed either for exchanging business documents in production networks that do not consider personalised products, or for addressing the specific needs of software service quality management. For this reason, appropriate data elements have been reused, but adapted or extended to enable their integration into manufacturing service descriptions supporting the customised configuration of agile production networks.

7.1.2. Integration into Agile Production Networks

In contrast to manufacturing service descriptions, complete definitions of agile production networks do not need to be exchanged between production network participants. However, related information must be modelled so that it can be handled by IT systems used to configure and operate agile production networks. Figure 7.4 shows the relationships between agile production networks, the manufacturing services and their dependencies involved, which are explained in the following.

It may be the case that the same process is integrated into multiple agile production networks, but configured with different parameter values. Consequently, references to manufacturing service instances representing configured, executable manufacturing services must be integrated into the agile production network structure instead of linking generic manufacturing service descriptions.

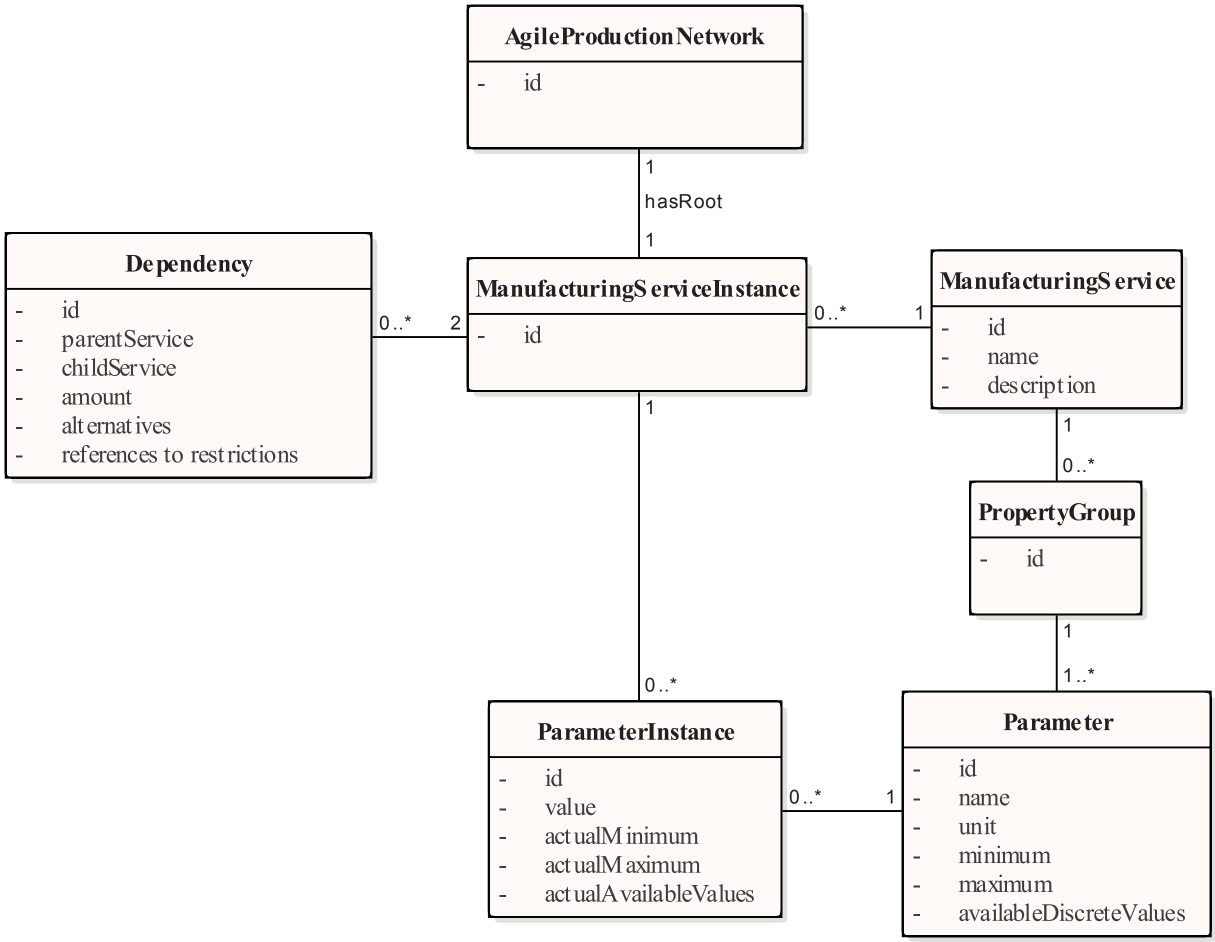

Figure 7.4. Model for representing agile production networks

The manufacturing service instances contain references to the related manufacturing services embodied by them. These serve as access points to general information about the manufacturing services, primarily providing organisations and category assignments. Additionally, manufacturing service instances state the specifically configured characteristics of an executable manufacturing service to be integrated into an agile production network. In detail, they reference respective parameter definitions, specify their values, and potentially further limit related restrictions, thus meeting the needs of the specific manufacturing service combination and related dependencies. Property groups do not require instantiation because the parameter instances refer to their generic definitions from the manufacturing service description and are thus already assigned to respective property groups.

When modelling an agile production network, a *root node* must be defined for its tree structure in the form of a manufacturing service instance, which uniquely identifies the final product to be delivered and ensures that there is only one process completing the overall agile production network operation. This simplifies the management and operation of agile production networks by IT systems, and addresses the need for clear responsibilities in the production network, e.g. for the delivery of the end-product.

Starting from the root node, the structure of an agile production network can be designed by establishing dependencies between manufacturing services, i.e. their instances. For this, dependencies must include references to parent and child manufacturing service instances (see section 6.3.1). All parent-child relationships between manufacturing service instances must fulfil the condition that each instance has maximum one parent, but may have various children. This results in the agile production network having a stringent tree structure. This tree structure defined by branches and levels of dependencies, as well as the integration of manufacturing services into it via specific instances, allows manufacturing services to be distinctly arranged, even when they are integrated into production networks several times, i.e. repeated at different stages in the product tree or applied to different branches of the tree structure, as is the case with grinding processes, which are executed in a sequence with increasingly fine-grained tools, or coating processes which are performed on several parts of a product before it is assembled.

7.1.3. Exchange, Management, and Storage of Data Elements

Manufacturing services, their configurations and combinations not only need to be modelled, i.e. represented by respective classes and their instances, but also be created, exchanged, managed, and stored by means of an appropriate software infrastructure in order to support the configuration of agile production networks with an IT system.

To aid this, appropriate JSON schemas are developed (see section 6.2.3), which need to be handled by the underlying IT infrastructure. The functionalities required for this must be implemented throughout all levels of the corresponding software system. Figure 7.5 illustrates the stack of software system components enabling to handle data elements consistently throughout all levels, from the databases used to store information and make it accessible for future usage up to the exchange of manufacturing service descriptions via web services and customer interactions.

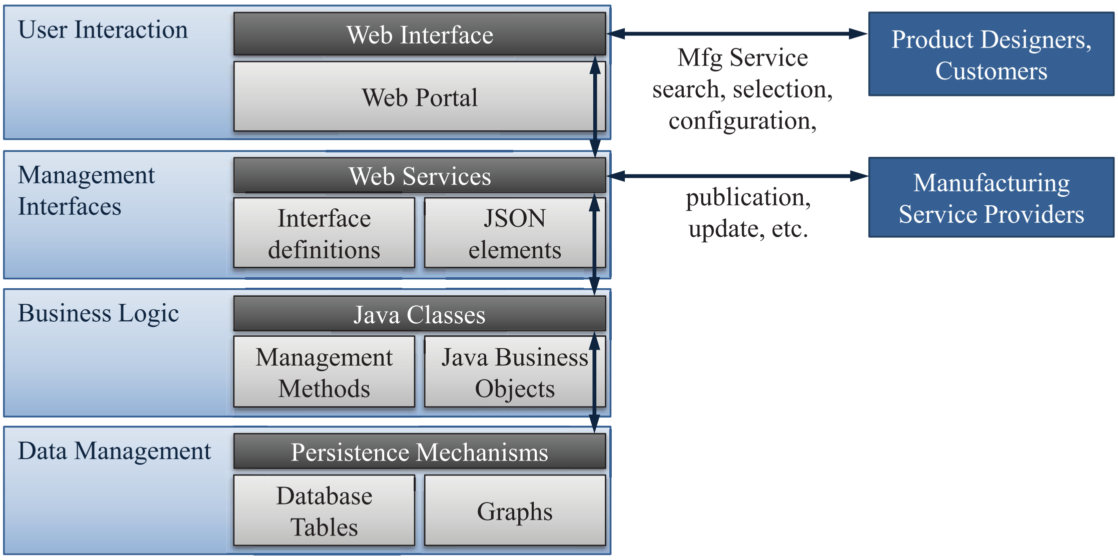

Figure 7.5. Manufacturing service model representations at different software system layers

The backbone of this stack of software components are Java classes, which are implemented according to the class models shown in figures 7.2, 7.3 and 7.4. They serve as the core of the implementation of manufacturing service descriptions, since they can be used to integrate libraries for generating the respective JSON documents and database tables. This is implemented using annotations, i.e. particularly marked comments which serve as commands for runtime environments, compiler, or application servers, but do not impact the actual program sequence (Daum 2007, pp. 181). The annotations integrated to the Java classes map JSON and database elements to Java classes and their attributes. In addition to representing the structure and contents of JSON documents and databases, Java objects can be directly processed by programs implementing the business logic to be applied to the respective data elements. This business logic provides functionalities for managing manufacturing services, as well as for establishing and administering agile production networks, related manufacturing service instances and their dependencies. These management methods supply interfaces to manufacturing service providers, product designers, or customers in the form of web services or Graphical User Interfaces (GUIs) which are able to handle or edit JSON documents specified by respective Java classes and their annotations. Figure 7.6 shows an excerpt of a manufacturing service description for the same sample used in figure 6.3 to illustrate the contents manufacturing service descriptions.

```
{ “manufacturingService”: {
    “id”: “2”,
    “name”: “OLED lamination”,
    “description”: “glues OLED elements between substrates”,
    “providingOrganisation”: {
        “name”: “OLED manufacturer A“,
        “industryBranch”: “Electronics”,
        “address”: “some street 21, 12345 some town”, ...},
    “category”: [
        {“id”: “27”, “name”: “lighting elements”},
        {“id”: “38”, “name”: “glueing (assembly)”}],
    “outputProperty”: [{
        “name”: “geometry”,
        “parameter”: [
            {“id”: “211”, “name”: “length”, “unit”: “mm”,
            “minimum”: “30”, “maximum”: “300”, null},...]}, ...],
    “inputProperty”: [{
        “name”: “base substrate”,
        “parameter”: [
            {“id”: “219”, “name”: “thickness”, “unit”: “mm”,
            “minimum”: “0.5”, “maximum”: “3”}, ...]}],
    “contract”: {
        “warranty”:[
            {“id”: “226”, “name”: “duration”, “unit”: “a”,
            “minimum”: “1”, “maximum”: “3”}, ...],
        ...}
}}
```

Figure 7.6. Excerpt from a JSON representation of a manufacturing service

The JSON representations of manufacturing services correspond with the UML class model defined in figure 7.2. They are used to publish respective contents to the production network management infrastructure by sending it as payload of a web service request.

After receiving a manufacturing service description via the web service interface, the business logic methods store it to the linked databases. This is achieved by appropriate persistence mechanisms implemented at data management level to control database access operations and the related mapping of database contents and Java objects. This takes place in both directions: Writing access and the transformation of information from Java objects to database contents is implemented to store, update or delete information, and reading access and reverse data transformation are supplied for executing queries. In doing so, general information about manufacturing services, especially about their providing organisation and properties, are stored in a relational database, i.e. in the form of tables. Information about the structure of agile production networks is held in a graph-based database, which corresponds with the related manufacturing service and dependency tree layouts. There, dependencies are implemented as edges, linking nodes that refer to manufacturing service instances.

In addition to this division of the representation and management of manufacturing services into the described horizontal layers, the technology stack is also divided into vertical segments. This allows each component of manufacturing service descriptions to be managed separately. As a result, providing organisations and categories can be managed independently of specific manufacturing services. This also conforms to the modularity of manufacturing descriptions, making them compatible with potential future extensions.

7.2. Establishing Application Contexts

As explained in section 6.3.1, the application context of manufacturing services is determined by assigning related product and process categories to dependencies in order to express pre- and post-conditions. These are the components and preliminary processes which provide the input required for a certain manufacturing service, or subsequent processes which are needed to complete it. The correctness and completeness of relationships between manufacturing services, and thus the structure of the agile production network, can be verified based on these application context rules. The following sections explain in detail how the concept for the dependency models and related reasoning mechanisms based on manufacturing service categories, which are outlined in sections 6.3 and 6.4, are implemented.

7.2.1. Category Structure

As mentioned in section 7.1.1, a specific manufacturing service category can be assigned to multiple manufacturing services, and vice versa. For this reason, as well as to address the need for categories to be uniquely defined, which is required to compare manufacturing services, these categories must be managed independently of manufacturing services. Furthermore, they must be positioned in a branched structure which defines parent-child relationships between categories, i.e. which subcategories belong to which specific category. This structure must be extendable to include additional product or process classifications, which may be provided in the future. Additionally, the category model needs to represent existing classifications, such as eCl@ss or GPC, to ensure conformity with standards. The contents of these standards, i.e. category numbers, names, and descriptions, can also be used to fill the related category database initially. Figure 7.7 shows the class model for representing manufacturing service categories, which results from these considerations.

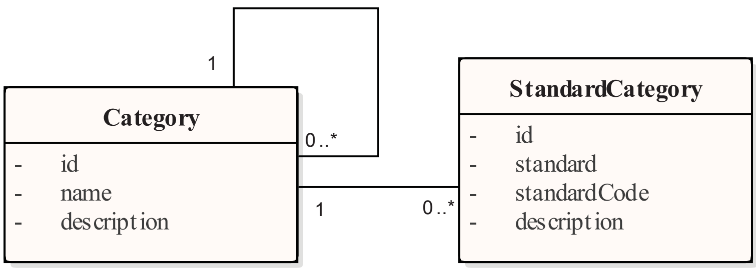

Figure 7.7. Category model

In addition to representing manufacturing service categories, their integration with sequences of manufacturing services must also be modelled to set respective application contexts (refer to section 6.3). This is achieved by extending the agile production network model from figure 7.4 with dependencies between categories, as shown in figure 7.8.

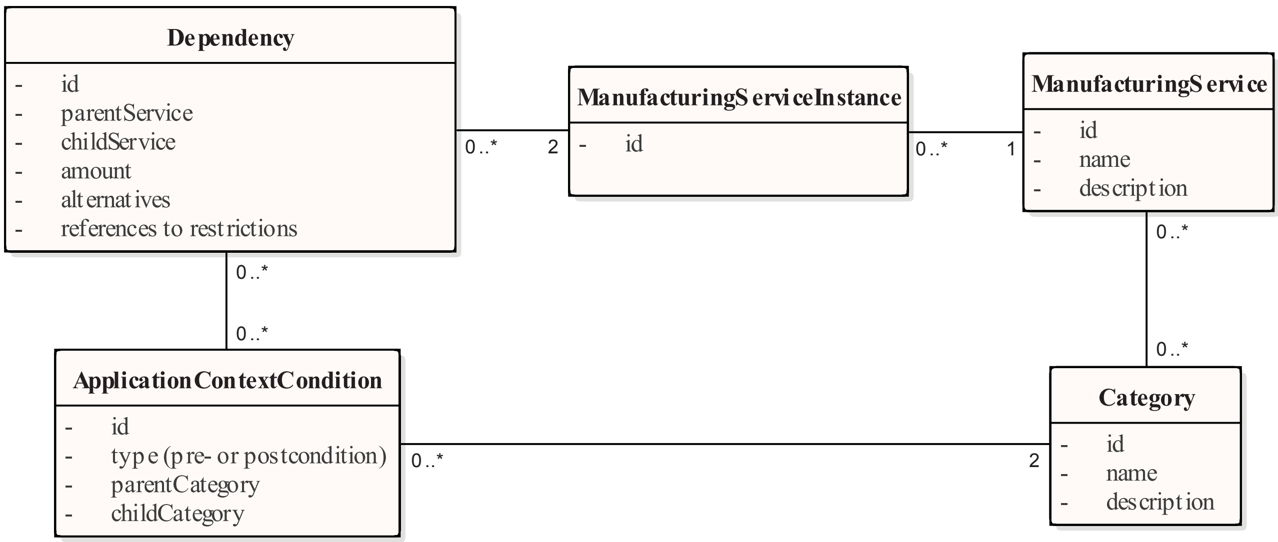

Figure 7.8. Integration of application context into the dependency model

In doing so, categories of interlinked manufacturing service instances are referenced via their generic manufacturing service description because categories are general classifications which cannot be instantiated.

Pre- and post-conditions for executing manufacturing services are added to the dependency model by means of *ApplicationContextCondition* objects, which allow optional or mandatory requirements on manufacturing service sequences to be specified. The contents of these pre- and post-condition elements are defined by references to two category instances: the source category, which is assigned to any manufacturing service for which the condition applies, and the destination category, which specifies the type of products or processes which must precede or follow this manufacturing service. An example is illustrated by the red arrow in figure 7.9.

As with the *Dependencies* forming manufacturing service trees, *ApplicationContextCondition* objects are implemented as edges in graphs where *Categories* are represented by nodes. Together with the bidirectionally branched structure of the category tree (see self-referencing category in figure 7.7), this results in a network of relationships between categories, as shown in figure 7.9. Classifying of

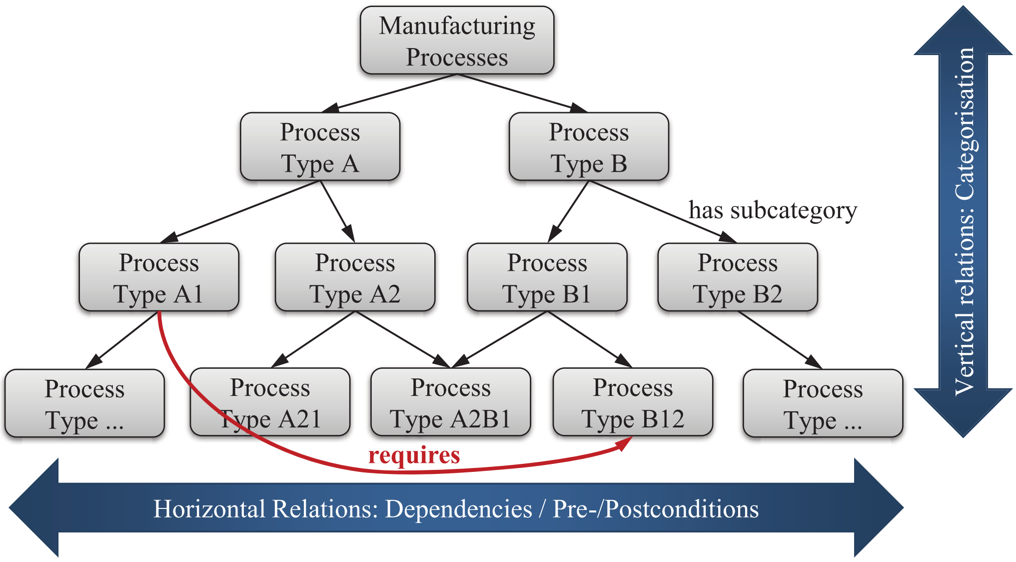

Figure 7.9. Relations between categories

categories with the aid of a branched structure results in vertical relationships between categories. The application context of manufacturing services, which defines required category sequences in agile production networks, is represented by horizontal relations. This two-dimensional network structure must be considered when assessing of manufacturing service combinations.

7.2.2. Assessment of Agile Production Networks Based on Categories

Based on the model described in the previous section, manufacturing service sequences are assessed based on categories by reasoning feasible category combinations from this model, i.e. from existing dependencies that include application context information. Appropriate reasoning mechanisms are implemented by applying sequences of queries to the database. The content of these queries and their combination to form complex reasoning mechanisms is explained in the following.

Appropriate manufacturing services y which can or need to be connected with a manufacturing service x selected for integration into an agile production network, can be derived by executing the following reasoning steps:

1. Directly matching manufacturing service categories: The result of this reasoning step is the amount of all manufacturing services Y, for which equation 7.1 is valid.

$$Y = \{\ y \mid T(y)\}; T(y) = (R_{requires}(c_x, c_y) \vee R_{requires}(c_y, c_x)) \\ \wedge(R_{hasCategory}(x, c_x) \wedge R_{hasCategory}(y, c_y)) \tag{7.1}$$

2. The set of results from the previous step can be extended by considering specialisations c_z of categories c_y, which results in the additional amount of relevant manufacturing services z (see equation 7.2).

$$Z = \{\ z \mid T(z)\}; T(z) = R_{hasChild}(c_y, c_z) \wedge R_{hasCategory}(z, c_z) \tag{7.2}$$

3. Similar to step 2, the number of categories, and thus related manufacturing services to be considered as reasoning results, can be extended by adding adjacent category nodes c_j of c_y to the query space by applying equation 7.3. This results in an amount of manufacturing services j whose categories are similar, i.e. potential alternatives to the ones of manufacturing services y.

$$J = \{\ j \mid T(j)\}; T(j) = R_{hasChild}(c_i, c_j) \wedge (c_j \neq c_y) \wedge R_{hasChild}(c_i, c_y) \\ \wedge R_{hasCategory}(j, c_j) \tag{7.3}$$

In the same way, the environment of c_x can be extended to increase the search space for relevant manufacturing service categories c_y by also considering subcategories (reasoning step 2) and adjacent categories (reasoning step 3) of category c_x in step 1.

The results of reasoning steps 2 and 3 can be extended iteratively by including the children of categories c_z identified in step 2 and adjacent categories of c_i (parent category as partial result of step 3), etc. To achieve valid results when executing these reasoning steps, the number of iterations to be performed has to be limited. It has to be considered that the appropriate maximum number of iterations n_{max} increases with the number of vertical edges in the category tree m, and with the level in the category tree m_y on which the directly matching categories c_y are found (see equation 7.4). The factor 0.5 is regarded as maximum applicable to achieve valid results. The reliability of results derived by executing such iterations increases with lower factors.

$$\begin{aligned} n \in \mathbb{N}; m \in \mathbb{N}; m > 1 \\ n_{max} \leq (m - m_y - 1) \cdot 0.5 \end{aligned} \tag{7.4}$$

To obtain an indication of the probability of connections to users who design products and configure related agile production networks, the results of these reasoning steps must be prioritised. This is achieved by combining conceptual ideas from neural networks and swarm intelligence algorithms, particularly by adding weighting factors, i.e. priorities, to the identified potential connections based on their distance from direct category matches. To implement this, intersections are created between different category result groups.

In doing so, the derived categories c are put into order according to their distance from those which have direct category matches. Furthermore, manufacturing service categories c_{y_1} to c_{y_l} are compared with each other to identify overlaps and refine the order of categories. The priority of manufacturing services y (for z and j accordingly) resulting from category-based assessment with one iteration is calculated according to equation 7.5.

$$\begin{aligned} c_y k \neq c_y l \\ A_1 = (Y_k \cap (Z_l \cup J_l)) \cup (Y_l \cap (Z_k \cup J_k)) \\ A_2 = (Z_l \cup J_l) \cap (Z_k \cup J_k) \\ A_3 = (Z_l \cup J_l) \cup (Z_k \cup J_k) \\ priority_a(y) = (y \wedge A_1) + (y \wedge A_2) + (y \wedge A_3) \end{aligned} \tag{7.5}$$

This is illustrated by figure 7.10, with area A_1 having the highest priority compared to other areas ($priority_{A_1} = 3$), i.e. it includes the most likely categories and related manufacturing services that can be connected to the manufacturing service x. Accordingly, the priorities of areas A_2 and A_3 correspond with lesser probabilities.

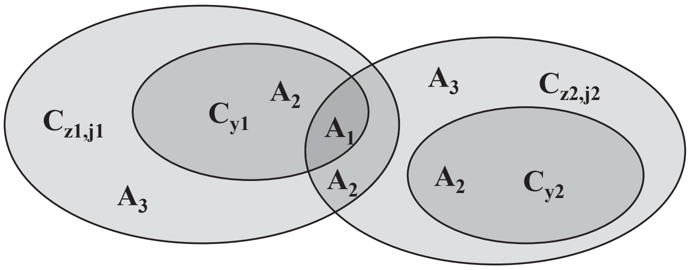

Figure 7.10. Prioritisation of reasoning results by means of intersections

In addition to considering query space intersections, the number of dependencies which combine manufacturing service instances of two specific categories is relevant when prioritising related reasoning results. Consequently, the relevance of each category environment c_y is rated by the number of connections which are established to it from a source of category c_x:

$$\begin{aligned} D_y = \{\ d(y) \mid T(d,y)\}; M(d) = 1 \\ T(d,y) = R_{hasSourceCategory}(d,c_y) \wedge R_{hasTargetCategory}(d,c_x) \\ \wedge(R_{belongsTo}(d,mi_y)) \\ priority_{cardinality}(y) = priority_a(y) \cdot |D_y| \end{aligned} \tag{7.6}$$

Figure 7.11 shows some excerpts of this incremental approach implemented to select potential manufacturing service categories and to prioritise them for suggestions. The queries listed there represent the steps for extracting all directly matching categories (and thus manufacturing services) for a certain category identifier in a first step. The search results are then extended by looking at their sub- and neighbouring categories following the reasoning steps explained above. To do so, the native query language of the graph database selected to store the data model, Cypher (see section 6.4.2) is used, i.e. configured and executed, by the Java business logic and persistence mechanisms.

Besides proposing and checking the application context of dependencies, i.e. the categories of their endpoints, the number of connections which need to be established for a specific manufacturing service during the configuration of agile

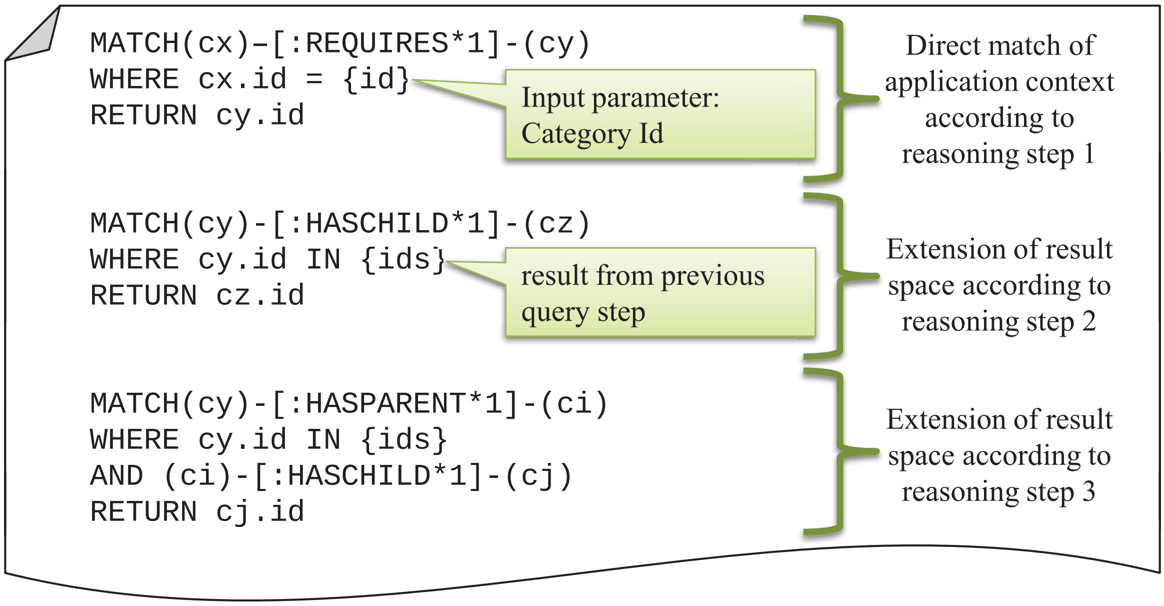

Figure 7.11. Query on category relations and prioritisation of results

production networks is validated. For instance, assembly processes require the inclusion of at least two components. To implement this, the amount of dependencies specified for previously defined manufacturing service instances mi_i of the same category or category group c_i is expressed by equation 7.7.

$$\begin{aligned} D_i &= \{\, d \mid T(d)\}; M(d) \geq 1 \\ T(d) &= R_{hasSourceCategory}(d, c_i) \wedge R_{belongsTo}(d, mi_i) \end{aligned} \tag{7.7}$$

The minimum of all cardinalities $|D_i|$ can be used as recommendation for the minimum number of dependencies to be established for a specific manufacturing service instance. This number, together with the prioritised category solution spaces c_y from above, serves as basis for assessing agile production network structures. The following sections describe how more details are added to these in order to refine results.

7.3. Detailing Reasoning Results Based on Involved Parameters

To improve the prioritisation of reasoning results for manufacturing service combinations based on manufacturing service categories (see section 7.2.2), the kinds of parameters related to the involved manufacturing services are considered. To do so, parameter categories are used to identify potential parameter restrictions, i.e. calculations and conditionals, to be implemented on parameters of linked manufacturing services.

7.3.1. Modelling of Parameter Categories

To utilise knowledge about property types when assessing dependencies between manufacturing services, category information must be assigned to parameters. For this, the parameter model is extended by a *ParameterCategory* element, as shown in figure 7.12.

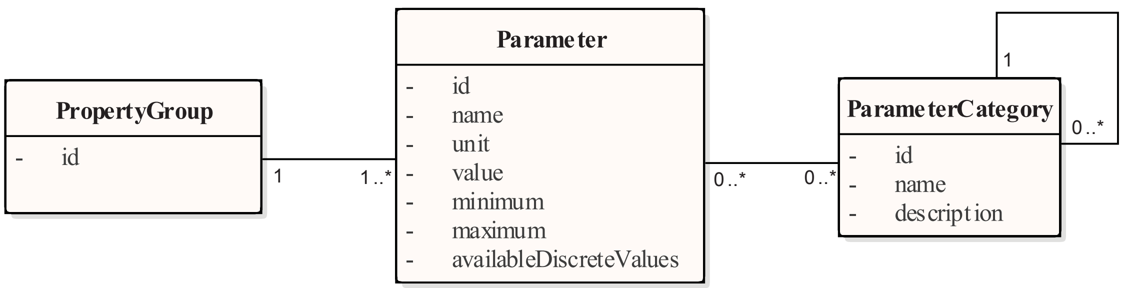

Figure 7.12. Integration of parameter categories into the data model

Like manufacturing service categories, parameter categories can be detailed in a branched structure that defines hierarchical relationships between parameter categories. For instance, parameters such as length, width, or curves, which define the dimensions and shape of a process result, can be assigned to respective parameter categories to ensure the comparability of manufacturing service characteristics. Additionally, these length, width, and curve categories may be subcategories of a parameter category geometry, whereas parameter categories like colour or patterns may belong to a parent category for optical properties.

To use parameter category information when assessing agile production networks, it must be integrated into the context of related application contexts and parameter restrictions. As shown in figure 7.13, this is achieved by referencing parameter categories via their related manufacturing service instances and parameters and comparing the results with parameter categories involved in previously defined dependencies. To enable this, *ParameterRestrictions* are implemented as connecting elements between related parameter instances, which additionally reference logical expressions from spreadsheets.

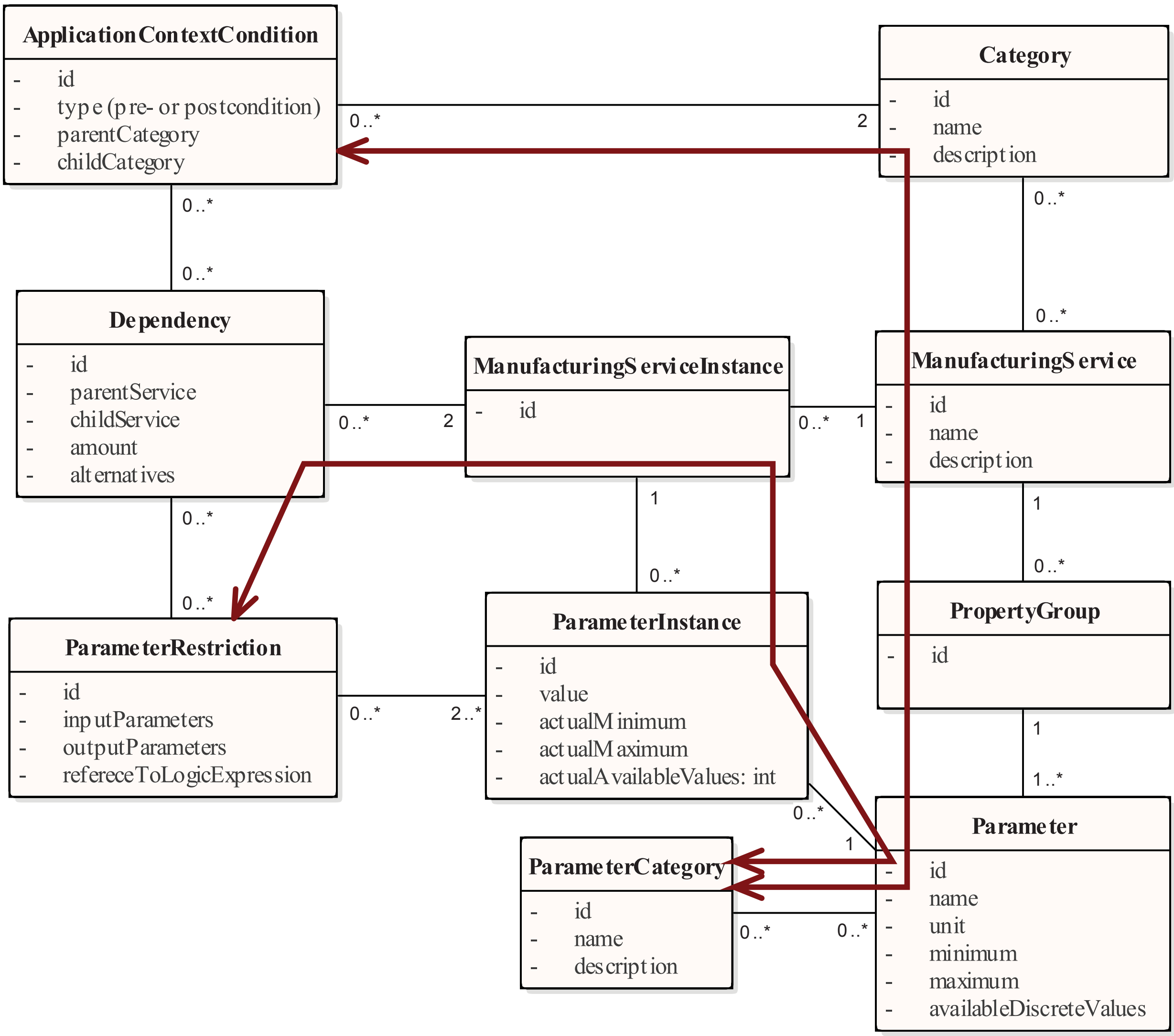

Figure 7.13. Integration of parameter categories into the context of dependencies

In contrast to assigning *ApplicationContextConditions* to dependencies in order to represent relationships between manufacturing service categories, there is no object designed which would directly integrate relationships between parameter categories into dependencies. This is because parameter categories serve as secondary information for further detailing the application context or definition parameter restrictions applicable to respective dependencies. Therefore, parameter categories are integrated into dependencies indirectly via related parameter instances for parameter restrictions, and via the chain of category, manufacturing service, and related parameters for application context conditions.

7.3.2. Increasing the Level of Detail of Reasoning Results

The parameter categories of manufacturing service input and output properties are mapped to identify potential connections, and thus improve the assessment of application contexts, as described in section 7.2. An example of this is the selection of an appropriate manufacturing service as input for a coating process which requires a specific surface structure. Possible options for manufacturing services to be linked to that service, which result from the category mapping described above, could be a grinding, polishing, or etching service. However, the quality of reasoning results, i.e. category matching, could be improved by comparing the properties of the process results achieved from those services with those specified as input parameters for the coating process. In this case, this means that if the coating manufacturing service has an input parameter belonging, for example, to the category “surface roughness”, all manufacturing services with output parameters of the same category are supposed to match better than others.

The comparison of parameter categories is used to extend the verification of application context conditions described in section 7.2.2 in order to improve its results. Therefore, it is implemented on the basis that there is a manufacturing service x for which manufacturing services y recommended for connection have been identified and prioritised by exploring the relationship $R_{requires}(c_x, c_y)$ between their categories c_x and c_y.

Assuming that a manufacturing service y belonging to category c_y is required as an input for a manufacturing service x from category c_x, the parameters of these manufacturing services $p_{y_{out}}$ and $p_{x_{in}}$ are derived by applying the conditions $R_{hasInputParameter}(x, p_x)$ and $R_{hasOutputParameter}(y, p_y)$. Vice versa, equivalent relationships $R_{hasOutputParameter}(x, p_x)$ and $R_{hasInputParameter}(y, p_y)$ apply if a manufacturing service from a category c_y must be executed after x.

For each of the resulting parameters p_x and p_y, the related parameter categories pc_x and pc_y are retrieved via the relationships $R_{hasParameterCategory}(p_x, pc_x)$ and $R_{hasParameterCategory}(p_y, pc_y)$ in order to compare them. If pc_x is equal to pc_y, the relationship between manufacturing services x and y is assigned a higher priority, since manufacturing service y implies that it will provide the kind of output required as input for manufacturing service x. However, not all input and output parameters of manufacturing services to be linked have parameter categories which correspond directly. For instance, the surface roughness achieved by a given manufacturing service may not only affect the required grain size, but also the time and force required for a subsequent polishing process. Therefore, relationships between parameter categories, which are specified in the context of already existing dependencies, are used to extend this matching mechanism. To do this, the involvement of parameter categories in parameter restrictions forming part of previously defined dependencies between manufacturing services is analysed, and the following condition checked. A parameter restriction pr_i, which is defined by dependency d ($R_{includesParamRestriction}(d, pr_i)$), must connect an input parameter of manufacturing service x with an output parameter of manufacturing service y. To be more precise, connections between instances of parameters pi and the respective manufacturing services mi have to considered: $R_{integratesOutput}(pr, pi_y)$ and $R_{integratesInput}(pr, pi_x)$. The relevant paramters p_y and p_x, and their categories pc_y and pc_x are derived from this. Finally, the parameter category pc_y of the output parameter p_y is treated as if it would match pc_x directly. These steps to enhance the relevant result space for the assessment are expressed by equation 7.8.

$$
\begin{aligned}
P_y = \{\ p_y \mid T_1(p_y) \wedge (T_2(p_y) \vee T_3(p_y))\} \\
T_1(p_y) = ((R_{hasInputParamenter}(x, p_x) \wedge R_{hasOutputParameter}(y, p_y)) \\
\vee(R_{hasInputParamenter}(y, p_y) \wedge R_{hasOutputParameter}(x, p_x))) \\
\vee(R_{hasParameterCategory}(p_x, pc_x) \wedge R_{hasParameterCategory}(p_y, pc_y)) \\
T_2(p_y) = pc_y = pc_x \\
T_3(p_y) = (R_{integratesOutput}(pr, pi_y) \wedge R_{integratesInput}(pr, pi_x)) \\
\vee(R_{integratesOutput}(pr, pi_x) \wedge R_{integratesInput}(pr, pi_y))
\end{aligned}
\tag{7.8}
$$

Furthermore, the range of relevant parameter categories can be extended by considering the environment of the parameter category pc_y in the related parameter category tree (see equations 7.9 and 7.10), similarly to extending the search space for manufacturing services based on their categories, as described in section 7.2.2, equations 7.2 and 7.3.

$$
P_z = \{\ p_z \mid T(p_z)\}; T(p_z) = R_{hasChild}(pc_y, pc_z) \wedge R_{hasCategory}(p_z, pc_z) \tag{7.9}
$$

$$
\begin{aligned}
P_j = \{\ p_j \mid T(p_j)\} \\
T(p_j) = R_{hasChild}(pc_i, pc_y) \wedge (pc_i \neq pc_y) \wedge R_{hasChild}(pc_i, pc_j) \\
\wedge R_{hasCategory}(p_j, pc_j)
\end{aligned}
\tag{7.10}
$$

In addition to using the categories of manufacturing services and parameters to detail reasoning results, the value ranges of respective parameters are considered to ensure that manufacturing services can be connected. For the parameters p_x and p_y, the respective minimum and maximum values are compared after converting their values according into the related parameter units if required. In doing so, the parameter ranges of the related parameters p_x and p_y must overlap, or the respective arrays of available discrete values must include matching values:

$$
\begin{aligned}
Y_{values} = \{\ y \mid T(y)\} \\
T(y) = (pv_y \in V_x) \wedge R_{hasValue}(p_y, pv_y) \wedge R_{hasParameter}(y, p_y)
\end{aligned}
\tag{7.11}
$$

Figure 7.14 and equation 7.12 visualise the steps to detail dependencies based on categories of manufacturing services and parameters, and mapping parameter values.

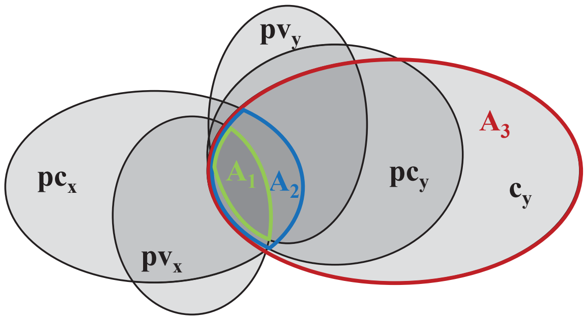

Figure 7.14. Further detailing of reasoning results

$$
\begin{aligned}
A_3 &= A_1 \text{ from equation 7.5} \\
Y = \{\ y \mid T(y)\};\ T(y) &= R_{hasParameter}(y, p_{y,z,j});\ p_{y,z,j} \in P_{y,z,j} \\
A_2 &= A_3 \cap Y \qquad (7.12) \\
A_1 &= A_2 \cap Y_{values} \\
priority_{total} &= priority_{cardinality}(y) + |A_1| + |A_2| + |A_3|
\end{aligned}
$$

For each step, overlaps between the specifics of the manufacturing services x and y are identified. These are then used as basis for the next intersecting step. As a result, manufacturing services with matching parameter values, parameter categories, and appropriate service categories (area A_1) are recommended with the highest priority, while manufacturing services with fewer overlaps, such as those from area A_2 for matching manufacturing service and parameter categories and area A_3 for manufacturing services from suitable categories only, are given lower priority. If the number of equivalent results is too high for manual assessment, they are further detailed by considering the number of matching parameter categories or values, which corresponds to the size of areas shown in figure 7.14.

7.3.3. Reliability of Reasoning Results

When determining overlaps of parameter categories and related values, and deriving related dependency recommendations, the amount of information available strongly affects the reliability of these reasoning results. This reliability depends on the following factors:

- The number of previously defined dependencies between manufacturing services, as they serve as knowledge base for suggesting potential future connections.
- The level of detail of categories assigned to the manufacturing services, since a more detailed specification of the manufacturing service to be linked allows contributing services to be selected more precisely. In this context, the granularity of the overall branched category structure also plays a role, since it affects the informative value of category mapping results, for which the neighbourhood of a certain category is considered.
- The proportion of a manufacturing service's parameters with matching parameter categories and values. This is related to the total number of parameters of a manufacturing service: The more details specified, the higher the number of matching attributes required to ensure a sufficient informative value of the matching result.
- The relevance and significance of a manufacturing service's parameters for the respective process or product. For instance, a manufacturing service may have optional or highly variable parameters which do not require to match well, whereas it may be essential for parameters representing key characteristics of the related process or product to match exactly.

From these considerations, it can be derived that the failure rate for reasoning results λ, which is inverse to the reasoning reliability, can be expressed by equation 7.13 with k being the number of previously existing dependencies and l representing the granularity of categories.

$$\lim_{k \to \infty} \lambda = 0 \text{ and } \lim_{l \to \infty} \lambda = 0 \tag{7.13}$$

It can be seen, that an infinite knowledge base would be required to eliminate potentially incomplete or incorrect recommendations. However, this is not applicable, since not all potential dependencies and subcategories for products and processes are modelled due to reasons of efficiency, and due to the intended purpose of the method and system, which is also to configure production networks for new individual products. Instead, the number of details of the manufacturing service to be connected, i.e. existing dependencies and category tree granularity, is compared with the respective average throughout the whole system.

Another way of expressing the estimation of failure rates of reasoning results is described by equation 7.14, with s representing the proportion of matching parameters in the total set of a manufacturing service's parameters, u the total number of parameters belonging to the manufacturing services intended to be linked, and t the overlap of parameter sets between new and existing dependencies. This relation can be detailed by considering the relevance and usage frequency of parameters for the respective process or product description by integrating a weighting factor w.

$$\lim_{s \to 1} \lambda = 0; \; s = \frac{t}{u} = \frac{\sum_{i=1}^{t} w_i}{\sum_{i=1}^{u} w_i} \tag{7.14}$$

7.3.4. Application of Reasoning Results

In the process of reasoning the feasibility of manufacturing service dependencies based on product and process categories, two objectives are addressed: the generation of recommendations, i.e. the identification of potential dependencies, and the verification of created dependencies in order to provide suggestions for improvement or issue warnings to product designers and customers. In both cases, reasoning based on the category network is executed in the same way, i.e. by analysing existing connections between manufacturing service categories. Whereas recommendations for dependencies result from a search for the most common connections between categories and manufacturing services, warnings are generated for connections between categories and manufacturing services which are located furthermost from these obvious connections. Thus, warnings indicating that customer-defined dependencies may not be feasible are generated by inversing the recommendation results. In the example from section 7.2.2, this means that they are issued for dependencies where the category c_y of the linked manufacturing service is located outside the solution space resulting from the described reasoning steps.

Due to the prioritisation and reliability estimation steps described in sections 7.3.2 and 7.3.3, a dependency between the manufacturing services x and y will be strongly recommended if there is an overlap in all prioritisation and intersection steps, as well as if the reliability of recommendations is estimated to be high based on the listed criteria. Accordingly, dependencies for which only subsets of the assumptions apply are recommended with reservations. Due to the inverse character of warnings, they are issued for connections between manufacturing services for which no or only small overlaps exist in previously defined configurations, especially in cases where the reliability of the assessment is thought to be high.

Apart from being used to prioritise potential links between manufacturing services, the method described for matching parameter categories and values can also be applied to identify parameters of linked manufacturing services for which parameter restrictions ought to be implemented. The conditions to be fulfilled for such recommendations are the same as those for recommendations of dependencies connecting manufacturing services: Parameter categories of the linked manufacturing services must match or be integrated into previously defined parameter restrictions, and their value ranges overlap.

The overall validation and verification mechanisms applied to the dependencies between manufacturing services focus on their contents and semantics. Validating the related syntax is not considered, since this is covered by the implementation of the underlying data structure in the form of the respective JSON schema and related validators. These are supplied via the agile production network infrastructure technology stack and are therefore automatically integrated into the respective system components.

7.4. Verification of Manufacturing Service Links Based on Parameter Restrictions

While manufacturing services are linked and the related parameter restrictions configured by product designers or customers, the feasibility of the whole process chain resulting from this must be ensured. To do this, not only must the probability and completeness of dependencies be checked as described in sections 7.2 and 7.3, but also their correctness and manufacturability regarding parameter configurations. This can be achieved by verifying parameters of a certain manufacturing service instance, i.e. configured values and value range boundaries, as well as the impact which they, together with the defined parameter restrictions, have on subsequent process steps. This section explains the expression, integration, and application of parameter restrictions implemented to support this objective.

7.4.1. Representation and Execution of Parameter Restrictions

As described in section 6.3.2, parameter restrictions are modelled by means of spreadsheets, which are used to configure calculations and conditionals expressing the relations between manufacturing service parameters. When configuring these parameter restrictions, it is necessary to reference respective parameters forming part of manufacturing service models. As explained in section 6.3.2, this is implemented by extending the technology stack from figure 7.5 with an RTD server which integrates parameter definitions from manufacturing services and their instances into calculations and conditionals in the form of spreadsheets (see figure 7.15). In doing so, it automatically refreshes the input parameters of the calculations and conditionals with values from parameter definitions, and forwards the output parameters from the formulas in the spreadsheet to the web service to update the data model in the graph database.

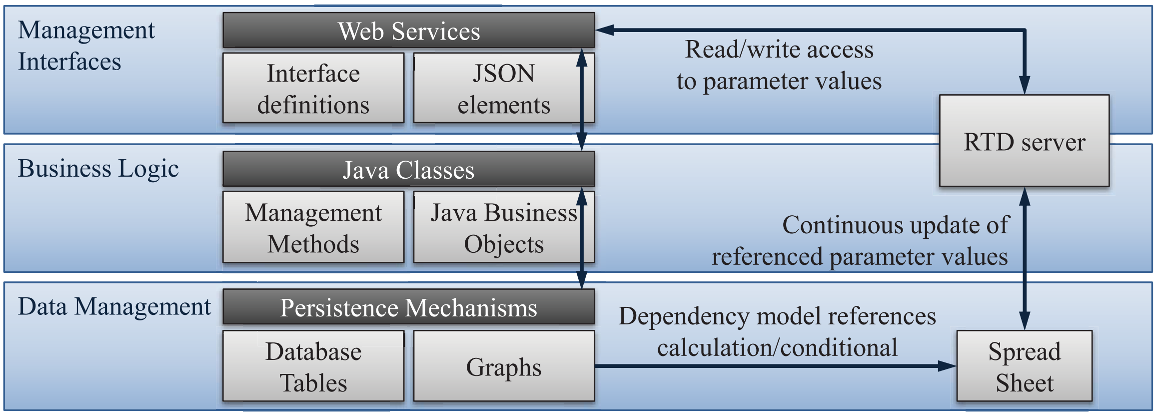

Figure 7.15. Manufacturing service model representations extended with expressions of parameter restrictions

To know which spreadsheet to use for which parameter restriction, these are referenced in the respective *ParameterRestriction* object (see figure 7.13, thus enabling the system to access and execute its contents if required.

For each parameter restriction, one spreadsheet is implemented which includes references to all related input and output parameter instances, as well as the calculation and conditional expressions linking them. Figure 7.16 shows the structure of these spread sheets. The parameter references handled there may not only point to actual values configured during the specification of personalised products, but also include related minimum or maximum values which are used to execute conditionals.

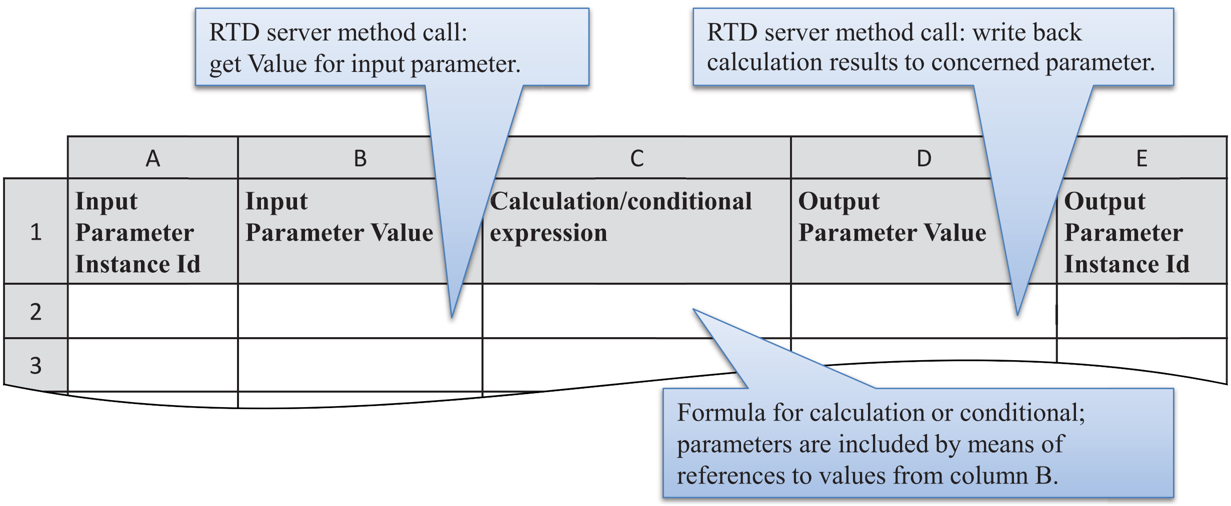

Figure 7.16. Spreadsheet for expressing parameter restrictions

In this way, both types of parameter restrictions, i.e. service-internal parameter dependencies and dependencies between parameters of linked manufacturing services, can be represented. However, the origin of parameter values needs to be differentiated: Parameter restrictions belonging to dependencies between manufacturing service instances in specific manufacturing service combinations must reference parameter instances, while dependencies between parameters of the same manufacturing service are implemented by referencing these parameters in general. These restrictions apply to all instances of a manufacturing service and its parameters, and therefore are instantiated together with them.

7.4.2. Verification of Parameter Restrictions

To verify a whole product tree or process chain that has been created by aggregating and individually configuring various manufacturing services, the parameter restrictions assigned to respective dependencies are executed incrementally. In doing so, the parameter value settings of the most granular manufacturing service instances, i.e. the sources of the overall production process, are used as input parameters for all related parameter restrictions. These include references to these parameters and are associated with the dependencies of the respective manufacturing service combination. The results of these parameter restrictions, i.e. their output parameters, are then used as input for parameter restrictions of the next dependency, which could also be a service-internal restriction calculating the output or limits of potential process results based on this input settings. The output of this restrictions is again used as input for the parameter restrictions of the next dependencies, and so on.

During each of these steps, the parameter restriction outputs, i.e. the parameter value settings for the following step, are compared to the range or set of available values valid for the related parameter. This workflow is also illustrated in figure 7.17. There, can be seen that the component for managing manufacturing service configurations and combinations and related dependencies plays a major role in this process. It executes queries on dependency trees to find parameter restrictions

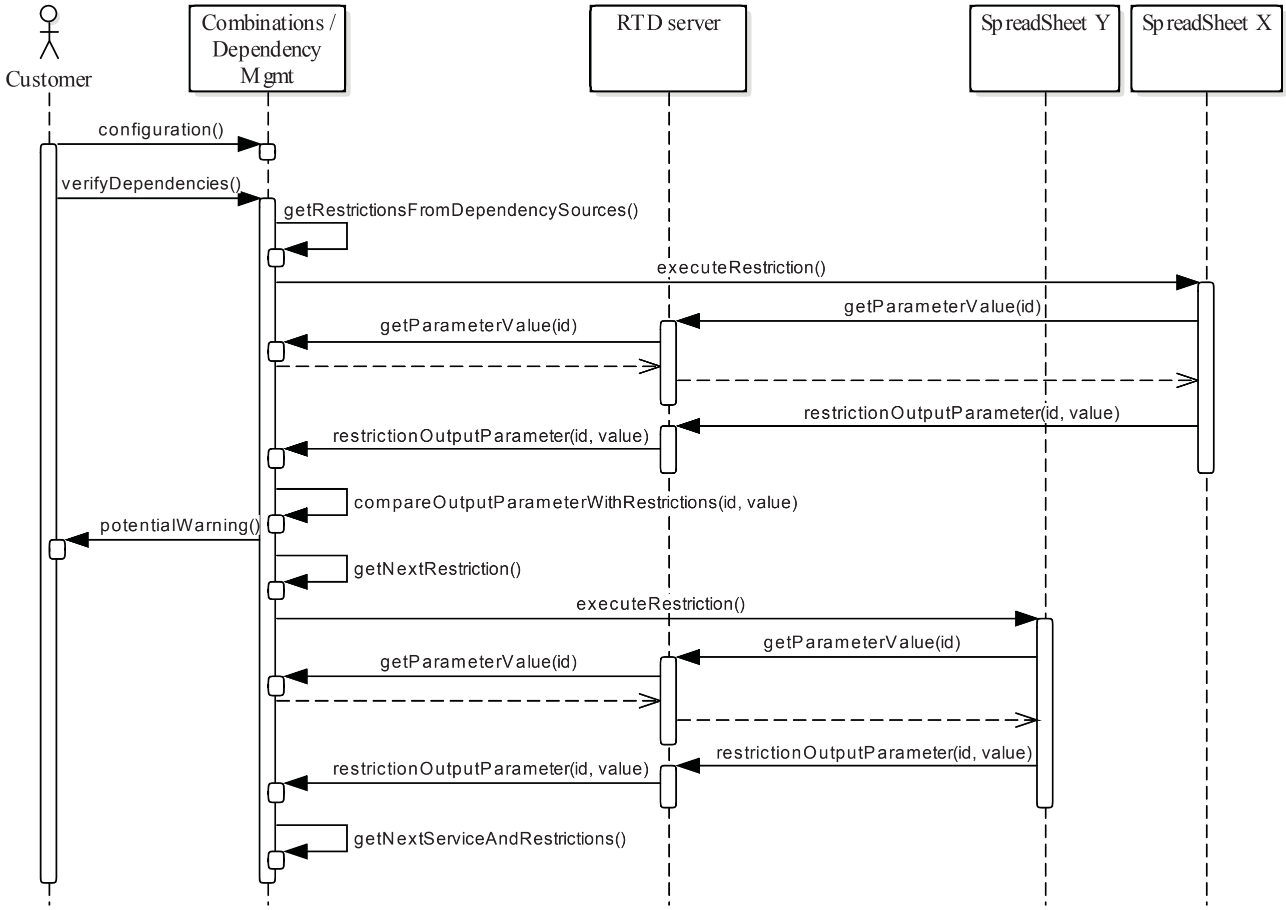

Figure 7.17. Workflow for the incremental verification of parameter restrictions

which need to be considered during the verification procedure. Furthermore, it extracts and specifies input parameters for the discovered restrictions, processes their output parameters for further usage, and determines the warnings to be displayed to customers based on conflicts between parameter settings and available discrete values or value ranges.

7.5. System Integration and Deployment

The overall IT system for modelling and linking manufacturing services in order to establish agile production networks consists of several modules, with each one managing respective information separately. Figure 7.18 gives an overview of the interaction between these components and the overall structure of the implemented software system. The arrows point to the components which other management components use by integrating them via respective web service interfaces. These web service interfaces are provided separately for all components

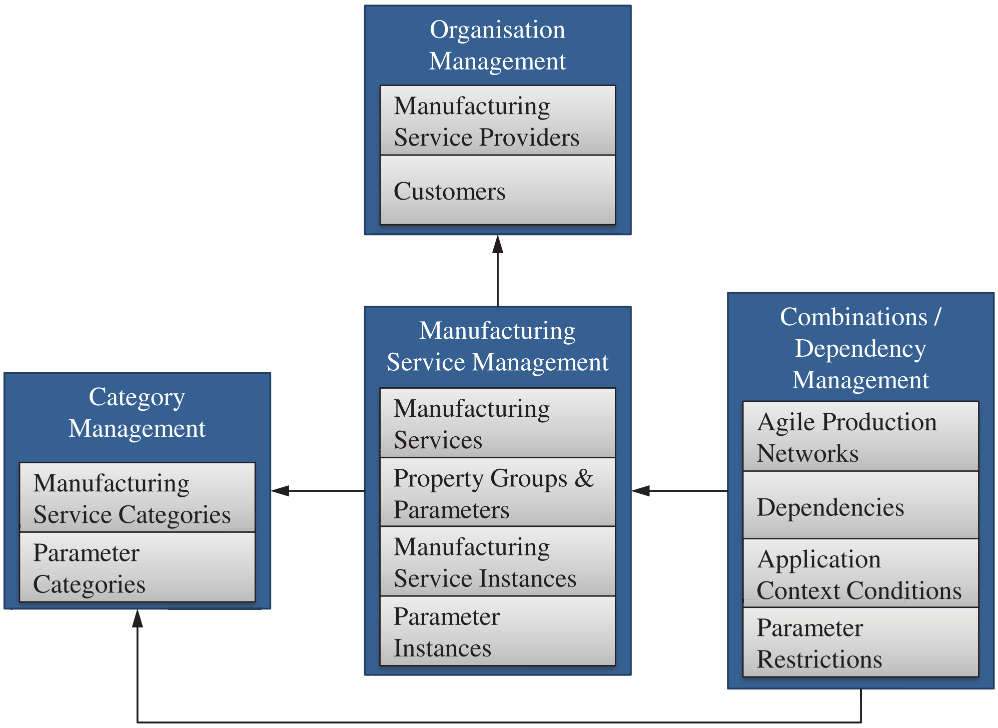

Figure 7.18. Software system components and interfaces

based on the technology stack shown in figures 7.5 and 7.15, which includes elements for database access, business logic, and user interaction via web services or GUIs, and is implemented for each component to manage related data models.

In addition to this basic functionality provided by all components for the respective data elements, the component for managing manufacturing service combinations and related dependencies is utilised to verify connections between manufacturing services step-by-step. This includes methods accessing the dependency model, such as the reasoning and assessment of dependencies based on manufacturing service and parameter categories as explained in sections 7.2 and 7.3, as well as the verification of parameter restrictions described in the previous section. The dependency management component provides separate methods to do so, including appropriate interfaces for each of these mechanisms. This enables users, i.e. customers, to select functionalities to be used according to their product and process knowledge.

To implement the recommendation, validation, and verification mechanisms for manufacturing service dependencies, the manufacturing service combination and dependency management component must closely interact with other components managing data related to manufacturing services and categories. To support that, these components provide appropriate persistence and search mechanisms via respective web service interfaces.

When implementing the overall software system, existing technologies, libraries, and frameworks have been used which contribute the following features:

- **Persistence mechanisms** for storing data models are implemented by using the standard Java libraries for Neo4j which enable to access the database and handle respective data objects without additional interfacing, parsing, and marshalling mechanisms.
- A **communication infrastructure**, including the provision of web services, related interfaces and JSON objects, as well as related data model transformation and syntax validation, is offered by Java API for RESTful Web Services (JAX-RS) libraries, which are integrated to the respective management components via annotations.
- These JAX-RS libraries also include a framework for implementing **security mechanisms** required when applying web services, primarily user authentication and encryption of messages or data elements by means of Secure Sockets Layer (SSL) certificates. Further security measures are implemented with Firewall settings and an Apache Webserver to restrict access to the overall software solution.
- A WildFly application server, which provides a **runtime environment** that enables IT services, i.e. the components shown in figure 7.18, to be deployed and operated, and accessed via the web.

Based on this technology stack, further features addressing industrial acceptance have been implemented. **Privacy**, i.e. the restriction of access to specific manufacturing service details, agile production networks, and order information to authorised users, is realised by linking system users to manufacturing service provider or customer objects which are controlled by the organisation management component. This link enables authorisation to be enforced directly when executing queries on the database. To do so, respective user and organisation variables are integrated during query creation in the form of additional conditions. **Responsiveness**, i.e. availability, connectivity, and performance of the overall system, can be maintained by deploying the overall IT system, including databases and application server, on a cloud environment. This also makes it easier to operate the system. To ensure **usability** of the overall IT system, a web portal serves as user interface for manufacturing service providers and customers as described by Yip, Jagadeesan et al. (2011). This web portal includes graphical front-ends for managing manufacturing services, establishing agile production networks, and handling related orders. Depending on the amount of information provided for each manufacturing service, the configuration and combination of manufacturing services can be supported by the graphical representation of the resulting product, as implemented by Yip, Corney et al. (2013).

8. Evaluation of Results

In the previous chapters, the objectives and requirements of agile production network management to support personalised production have been analysed, and a method, model, and IT system have been developed to configure and combine manufacturing services respectively. To evaluate the overall fulfilment of the objectives and requirements by the developed method, model, and IT system, the following sections describe the procedure for testing these developments and present the related assessment results.

8.1. Evaluation Criteria and Selection of the Application Example

The method and system implementation described in this thesis are evaluated based on the objectives and requirements identified in chapter 3, which are compared to the features of the developed method, model, and IT system. The fulfilment of most of these requirements can be assessed straightforwardly by analysing the respective model and system components. However, especially when it comes to the fulfilment of the method objectives in general, primarily the reduction in efforts to configure agile production networks, it is not possible to measure and assess it in that way. Therefore, an application example is used to evaluate the benefits of the method and supporting system related to method objectives and industrial success criteria.

The most important criterion for selecting this application example is the need to implement an agile production network. Consequently, the product must require to be personalised, and the related manufacturing infrastructure should supply maximum customisation options when implementing the application case. Furthermore, in line with the focus of the method, which is on the configuration of agile production networks, i.e. combination of manufacturing services, the production of the personalised product should require the involvement of multiple manufacturing services executed by different production sites or companies. An application example from the organic semiconductor industry was chosen, which includes process steps with different degrees of automation and flexibility. It also encompasses the possibility to vary the number of manufacturing service instances to be integrated in order to reflect variations in product complexity. This allows developments to be assessed with regard to industrial context variations.

The quantifiable benefits of agile production network participation strongly depend on the specific application case and the business context of the involved companies. Therefore, the method and system objectives were tested and evaluated to prove the concept and obtain qualitative results. For this reason, the evaluation does not consider the quantitative measurement or calculation of Key Performance Indicators (KPIs) like return on invest. Instead, it estimates the fulfilment of business objectives based on the "Net-Check" approach of Schuh, Boos et al. (2009). Thus, it identifies the main benefits of agile production networks as well as efforts required to configure them with and without using the method and IT system and puts the results in relation to each other.

8.2. Fulfilment of Requirements

The fulfilment of the requirements on the method, model, and system is explained in tables 8.1 and 8.2, which outline corresponding solutions and include references to the sections giving details of their implementation.

Requirement	Solution / method features
`Req01`: Description of modelling procedure	Explained by the method stages *strategic considerations*, *analysis and modelling*, *defining objectives*, and *connecting manufacturing services* (5.2–5.5)
`Req02`: Description of model transformation	Derivation of recommendations and warnings by assessing dependencies between manufacturing services (7.2, 7.3, 7.4, and 5.5).
`Req03`: Description of model usage	Using data structures and contents when connecting manufacturing services, especially if aided by assessment features (5.5)
`Req04`: Modelling language	Data models / JSON structures for representing manufacturing services and dependencies (6.2.3)
`Req05`: Integrated modelling language and procedure	Usage of data models for manufacturing services and dependencies during method application (see fulfilment of **`Req01`**, sections 7.1.1, 7.2.1, and 7.3.1).
`Req20`: Integration into factory-internal processes and infrastructures	Extraction of manufacturing service details from production infrastructure (5.3). This is fulfilled in principle, but additional mapping mechanisms and tools are necessary to automate the extraction and exchange of manufacturing service descriptions and availability information.
`Req21`: Integration with product and process design	Definition of the product idea (5.4) and configuration of parameters to implement it (5.5); option to integrate manufacturing service descriptions directly into respective product configurators (7.5).
`Req22`: Compatibility with existing standards	Integration of product and process classifications into manufacturing service categories (7.2.1); Model for information about participating organisations on the basis of the myOpenFactory standard (7.1.1), which also provides a document structure for order processing.

`Req23`: IT security and privacy	Standard security solutions as they are part of the framework used for system implementation; authorisation is enforced during database access by extending respective queries with user and organisation information (7.5).
`Req24`: Responsiveness and usability	Availability and short response times are achievable through cloud deployment; web portal for user interaction, into which graphical interfaces for product configuration can be integrated (7.5).

Table 8.1. Fulfilment of requirements on the method

Requirement	Solution / model and system features
`Req06`, `Req07`, `Req08`, `Req09`: Manufacturing service model, Parameterisation, and dependencies between parameters	Manufacturing service data model, including properties and their customisation options (available parameter ranges and discrete values), contractual terms, and service-internal parameter restrictions (7.1.1).
`Req10`: Flexible level of detail for manufacturing services	Manufacturing service descriptions allow different granularities (7.1.1); selection of appropriate level of detail described in respective method stage (5.3).
`Req11`: Online availability of manufacturing services	Contractual terms integrated into the manufacturing service model as a separate item (7.1.1), which can be regularly updated without affecting other aspects of the manufacturing service description.
`Req12`: Common access point for manufacturing services	Manufacturing service management component which, among others, serves as common manufacturing service repository (7.5).
`Req13`: Comparability of manufacturing services	Manufacturing service and parameter categories to align the interpretation of products, processes, and their properties (7.2.1 and 7.3.1).

Req14, **Req15**, **Req16**: Separate model for defining dependencies between manufacturing services, expression of dependency rules	Dependency data model (7.1.2), including application context and parameter restriction expressions (7.2.1 and 7.4.1).
Req17, **Req18**: Gather knowledge from existing configurations, derive suggestions and assess feasibility of dependencies	Application context assessed based on manufacturing service and parameter categories from previously defined dependencies (7.2.2 and 7.3.2); parameter restrictions assessed based on parameter categories, applicable value ranges, and spreadsheet rule execution (7.3.2 and 7.4.2).
Req19: Extensibility of the knowledge base	Storage of newly created manufacturing service descriptions and categories to the common repository (7.5 and 5.6).

Table 8.2. Fulfilment of requirements on the model and system

As shown by this assessment, all requirements on the method, model, and system are fulfilled by the developments. The fulfilment of requirements **Req20**, **Req21**, **Req23**, and **Req24** could be improved when the IT system is further refined for industrial application. This would include extending security mechanisms to prevent injection attacks, or strengthening the system's position as a single point of interaction for users by smoothly integrating the method and system into factory-internal processes and tools, as well as with graphical product design tools, which are commonly used for product specification. However, additional mapping mechanisms or interfaces would be required, which would need to be adapted to the specific needs of the respective industry sector or company.

8.3. Filled Research Gaps

In addition to validating the fulfilment of requirements, the impact of the developed method, model and system on the research gaps identified in chapter 4 has been evaluated as it can be seen in table 8.3.

State of the art	Progress beyond
Description of manufacturing services	
Product-based models for the description of geometries such as STEP, IGES, or DXF	The developed model structure includes product and process aspects, as well as their classification, customisation options, and contractual details at the same time and in a human and machine-readable format, thus enabling users to create or use the contained information without shifting between multiple models or even systems.
Semantic-based manufacturing system and process descriptions as developed by (Negri, Fumagalli et al. 2016, Hoffmeister 2013, Ameri, Urbanovsky et al. 2012)	
Representation of contractual information of web services (Keller and Ludwig 2003) and text-based service descriptions as provided by USDL (Kiemes, Novelli et al. 2012)	
Configurability of product specifications is achieved by STEP extensions (Pratt, Anderson et al. 2005) or X3D applications (Yip, Corney et al. 2013), production processes can be configured using variables and boundaries as described by (SiLA 2013, Konrad 2012, SEMI E139-0709).	

<table>
<tr><td colspan="2">Classification of manufacturing services</td></tr>
<tr><td>Semantic categorisation approaches (Lu, Shao et al. 2014, Tao, Zhang et al. 2012, Giess, McMahon et al. 2009) are limited to related system boundaries.</td><td rowspan="2">The developed category model enables the integration of classification standards to the category tree, thus combining the advantages of existing systems, extendibility and validity beyond system boundaries.</td></tr>
<tr><td>Relevant standards are classifying industrial sectors, products, and manufacturing processes (NACE, ISIC, CPC, eCl@ss, DIN 8580:2003-09).</td></tr>
<tr><td colspan="2">Combination of manufacturing services</td></tr>
<tr><td>Orchestration of IT services by means of SoA-based workflow definitions such as BPMN, WS-BPEL, XPDL, YAWL, or ESB configurations</td><td rowspan="2">The developed solution combines the representation of knowledge about manufacturing service capabilities and dependencies which apply to connections of them. As a result, it enables the flexible combination of manufacturing services similar to existing solutions for IT service orchestration.</td></tr>
<tr><td>Product-oriented production configuration focusing on parameterising single production systems (Ostgathe 2012, Bengel 2010), or workflow definition and execution focusing on factory-internal product routing (Pfrommer, Stogl et al. 2014, Muckenhirn 2005)</td></tr>
</table>

Knowledge management for agile production networks	
Models for product and process constraints focus on the determination of manufacturability in previously dedicated production systems (Hotz, Felfernig et al. 2014, Shukor and Axinte 2009).	The manufacturability assessment of customer-specific manufacturing service configurations and combinations by means of a knowledge-based reasoning mechanism validates the feasibility of single components or process steps as well as completeness and correctness of dependencies.
Assessment of connections, mainly in the form of semantic match-making between manufacturing services, does not include the validation of completeness and feasibility of connections (Ameri and Patil 2012, Cai, Zhang et al. 2011, Jang, Jeong et al. 2008).	
IT solutions for agile production networks	
Existing IT solutions address subsets of the objectives, e.g. web-based market places and semantic match-making mechanisms (Ferreira, Sarraipa et al. 2014, Ameri and Patil 2012), as well as workflow configuration and service orchestration (Schulte, Hoenisch et al. 2014, Wang and Xu 2013, Rauschecker, Stöhr et al. 2013, Ameri and McArthur 2013, Rahman, Sadik et al. 2008) which are implemented as centralized or agent-based systems.	One integrated solution covering the whole process from modelling knowledge about manufacturing services to utilizing the knowledge while individually configuring and combining manufacturing services.

Table 8.3. State of the art and progress beyond

This progress beyond the state of the art includes developments closing the research gaps summarised in section 4.6:

- An integrated, holistic manufacturing service model, which includes related parameterisation options and restrictions
- Representation of dependencies and constraints which apply to combinations of manufacturing services
- Manufacturability assessment of customer-specific manufacturing service configurations and combinations by means of validating completeness and correctness of dependencies

These developments are applied in the context of a method for guiding manufacturing service providers and customers through the process of agile production network configuration by means of appropriate models and tools.

8.4. Application Case "Organic Semiconductors"

To assess the developments and the achievement of business objectives in practice, the method, model and system have been tested in the application context of the European research project ManuCloud (Meier, Seidelmann et al. 2010), which dealt with the provision of a manufacturing-as-a-service infrastructure for customisable organic semiconductor products. The manufacturing services considered in this project provide organic LED (OLED) and photovoltaic (OPV) elements, as well as lamination and framing processes to assemble glass substrates, OLED, and OPV elements. These manufacturing services were stored to the common manufacturing service repository and used to specify customer-specific facade elements (see figure 8.1).

During the evaluation, the related manufacturing service combinations were used to extract previously defined dependencies to assess the feasibility of a newly created combination. For this new manufacturing service combination, an individual

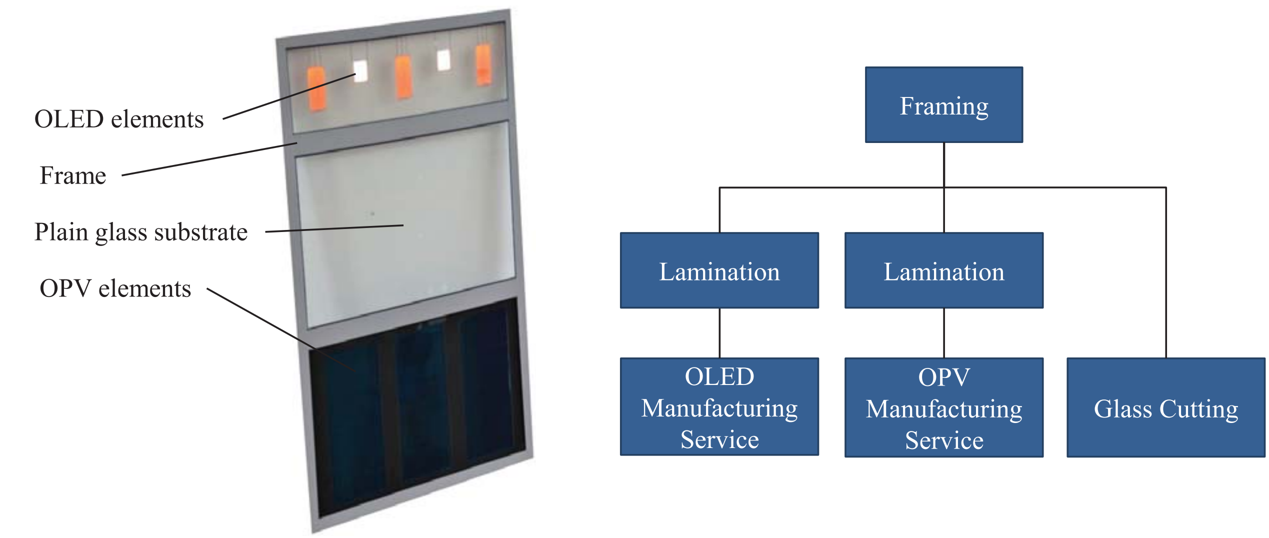

Figure 8.1. Facade element (left) and related manufacturing service tree (right)

product was specified in the form of a room divider, which is produced by a subset of the same manufacturing services as the facade elements, i.e. OLED elements which are laminated and framed.

The achievement of the method objectives was evaluated by analysing the efforts and know-how required to model, configure, and combine manufacturing services. These mainly depend on data structures, user interfaces, and the quality of reasoning results. To evaluate the latter, i.e. the reliability of dependency assessments, the manufacturing service repository was extended with additional products and processes which were not meant to be integrated to the actual room divider configuration. These have different categories with varying analogies to the ones to be connected.

8.4.1. Modelling and Provision of Manufacturing Services

A precondition for configuring and combining manufacturing services is that the required manufacturing services are modelled and made available via the common manufacturing service repository. Table 8.4 gives an overview of some typical properties of the OLED, OPV, lamination, and framing processes and their available values, for which manufacturing service descriptions have been created.

	OLED	OPV	Lamination (and framing)
Length (mm)	min: 75, max: 150	min: 300, max: 1200	min: 500, max: 1840
Width (mm)	min: 50, max: 76	min: 290, max: 330	min: 400, max: 1000
Shape	any 2D-Layout	any 2D-Layout	rectangle
Thickness (mm)	1.9	0.5	min: 10, max: 16
Colour	white, blue, orange, green	blue, green	–
Transparency (%)	min: 0, max: 45	min: 0, max: 20	–
X-Position child service n (mm)	–	–	min: 15, max: 985
Y-Position child service n (mm)	–	–	min: 15, max: 1825

Table 8.4. Excerpt of organic semiconductor manufacturing service properties

The shown properties mainly cover geometric and optical characteristics of the resulting products, since these are most relevant to the customer-specific design and process configuration. The full range of properties modelled for the OLED, OPV and lamination and framing processes is described in appendix A. These models, including internal parameter restrictions, represent the product and process know-how of the manufacturer which is relevant in the context of the application example. They have been created by process experts from the manufacturing service providers using a graphical user interface (see figure 8.2). In this way, the developed JSON structures were filled as input for the manufacturing service management component inserting the contents to the common database.

To represent the internal parameter restrictions which apply to the manufacturing services, respective spreadsheets were filled in and referenced from related dependency models. Figure 8.3 shows an excerpt of such a spreadsheet containing the calculation of an OLED's energy consumption from the example explained in section 6.3.1 (equation 6.3). In addition to the parameters as such, the models described in appendix A also list the calculations and conditionals which apply to them.

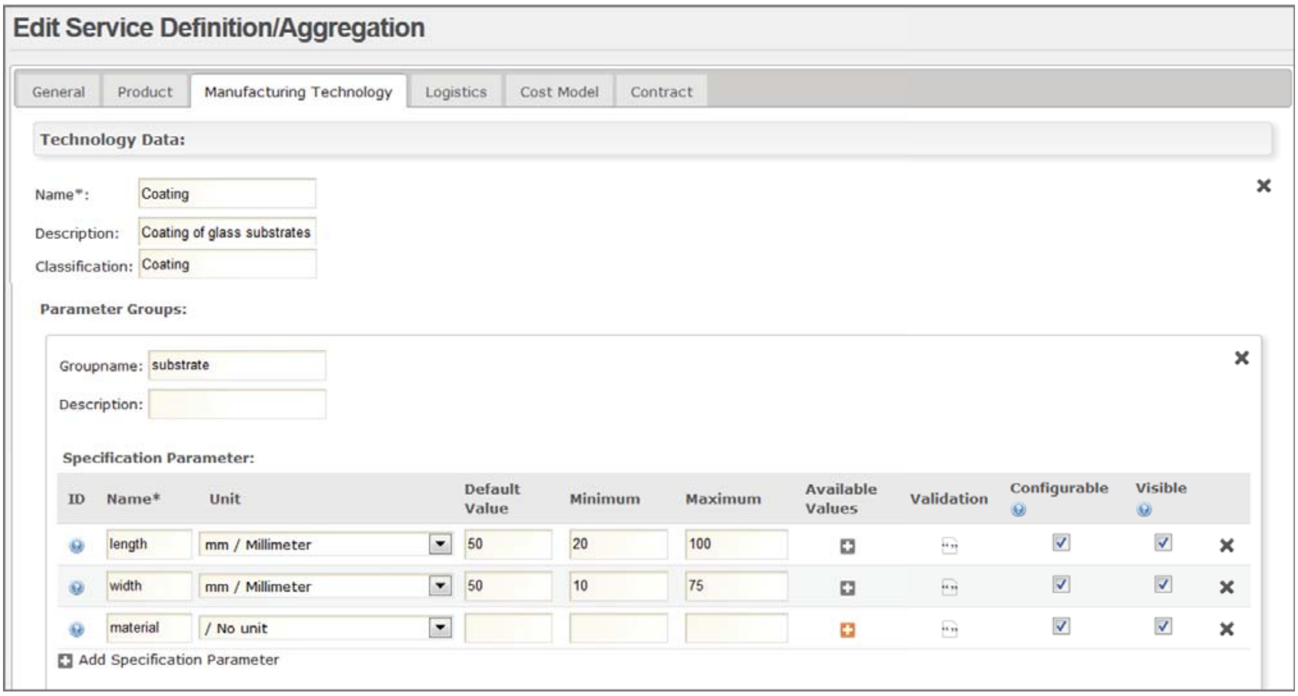

Figure 8.2. Web interface for inserting manufacturing service characteristics

	A	B	C	D	E
1	**Input Parameter Instance Id**	**Input Parameter Value**	**Calculation/conditional expression**	**Output Parameter Value**	**Output Parameter Instance Id**
2	38	=RTD(“rtd.progid”; ; A2)	=IF (OR (B2=“white”; B2=“blue”); (B3·2.308/100); (B3·1.846/100))	=RTD(“rtd.progid”; ; E2;C2)	35
3	29	=RTD(“rtd.progid”; ; A3)			
4	...				

Application of different constants, depending on the actual value of the parameter with Id 38.

Figure 8.3. Excerpt of a parameter restriction defined for the OLED element

8.4.2. Connecting Manufacturing Services and Assessing Dependencies

The facade element and room divider both consist of OLED elements which are laminated and framed (see figure 8.1). To generate the respective manufacturing service tree, in a first step appropriate manufacturing services providing organic semiconductor and assembly processes were selected from the common manufacturing service repository. After making this selection, a further manufacturing service was created for which parameters were configured in the same way as for single manufacturing services, i.e. via the GUI shown in figure 8.2. The parameters of the manufacturing services were integrated into calculations and conditionals in order to model parameter dependencies throughout the manufacturing service tree for the facade element. The knowledge modelled in this context is detailed in appendix B.

The dependency assessment mechanisms were tested by inserting additional manufacturing services into the service repository and selecting them when combining manufacturing services for the room divider. These additional manufacturing services were assigned to product or process categories or described by types of properties differing from those connected previously when specifying the facade element. Furthermore, a replacement for the OLED process was implemented which has the same categories and property types, but different parameter value ranges.

Testing has been restricted to the provocation of warnings, since recommendations and warnings are generated based on the same query mechanisms, and efforts and know-how required to connect manufacturing services for this relatively simple product are not expected to be reduced drastically by recommendations. In alignment with the assessment mechanisms for manufacturing service dependencies, the tests have been divided into two main test steps:

1. Selecting and connecting manufacturing services from the common repository: The compatibility of product and process categories, parameter categories, and related value ranges was checked by the developed system as described in sections 7.2.2 and 7.3.2. To do so, this process was repeated for several different manufacturing service combinations. In particular, the OLED manufacturing service was replaced by manufacturing services, which are either assigned to different categories or specified by properties differing from the ones of the organic semiconductor processes previously integrated into facade element specification.

2. Establishing and verifying parameter restrictions: The quantity, position, and shape of OLED elements to be installed in the room divider affect its size and shape. Accordingly, parameter restrictions were implemented to adjust the related minimum and maximum values. To check their feasibility, the verification mechanism described in section 7.4.2 was executed and the derived warnings compared with the intended results, especially for those restrictions which were designed to exceed respective limits for this purpose.

As a result, warnings were generated for the combinations of manufacturing services created during the evaluation as shown in the overview given by table 8.5.

Manufacturing Service \ Warning Type	Differing category	Differing properties	Exceeding parameter limits (from parameter restrictions)	Warning Priority
Drilling	X	X	X	A
Substrate Coating	X			B
Organic Semiconductor Process specified by used materials		X		B
Process providing OLEDs of different sizes				0
OLED Process involved in facade element specification				0
OLED with geometry exceeding lamination / framing limits			X	n.a.

Table 8.5. Overview of organic semiconductor test case results

8.4.3. Know-How Maintained in the System

When executing the method in the context of the application example, know-how of experts in semiconductor products and processes has been modelled, stored, and used for assessing combinations of manufacturing services by applying the developed system. These models cover OLED and OPV product and process characteristics including their customisation options and restrictions which are determined by the manufacturing equipment of the involved manufacturing service providers. The manufacturing service descriptions and service-internal dependencies representing them were filled by the experts and stored to the system in order to supply them to agile production networks later on. In the same way, the application context of these manufacturing services was modelled by the experts to ensure that their know-how about pre- and postconditions to be fulfilled by product trees or sequences of manufacturing processes can be applied to agile production networks to which the manufacturing services modelled by them are integrated later on. Furthermore, the combination of manufacturing services forming a facade element was implemented by the experts to provide a first set of dependencies serving as knowledge base for assessing further ones created by non-experts. Details of the modelled manufacturing services and dependencies, i.e. the knowledge of product and process experts gathered in the system, are listed in appendix A and B.

By storing the models to the knowledge base, they were made available to other system users, especially to those with less product or process know-how, via the system.

8.4.4. Evaluation of Benefits

In addition to the verification of the fulfilment of functional requirements of the method, system, and model, the benefits of the developments regarding business objectives were evaluated by potential users of the method and system. Especially manufacturers operating highly configurable manufacturing equipment were identified as relevant stakeholders, as well as persons and companies acting as designers on behalf of end-users.

Since the monetary quantification of the benefits of agile production networks and the related method and system cannot be calculated directly, the "Net-Check" approach developed by Schuh, Boos et al. (2009) was applied, which quantifies benefits of cooperations between companies and efforts involved in their establishment and utilisation by means of ordinal scales. Figure 8.4 outlines the steps to be conducted when applying this method.

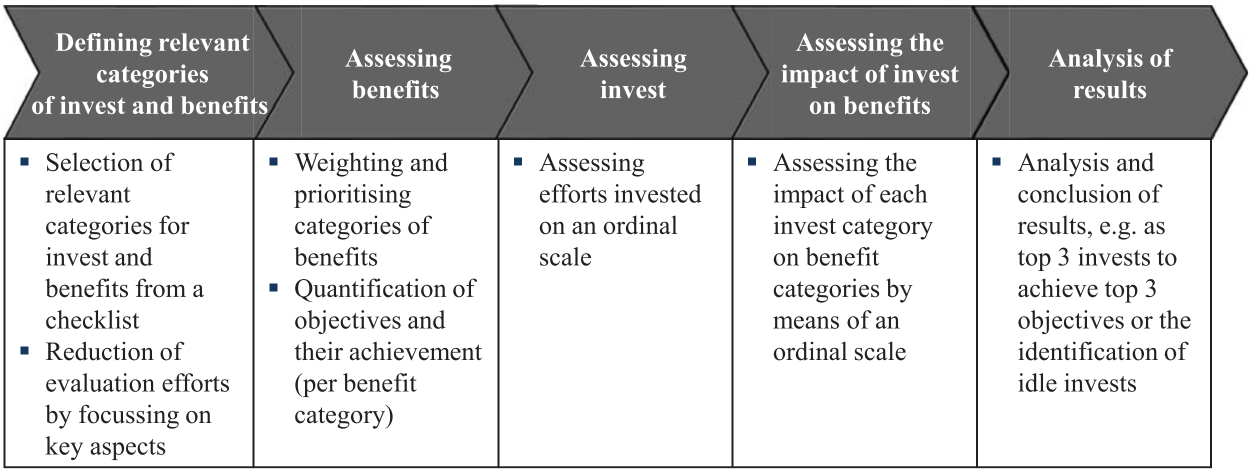

Figure 8.4. Overview of the "Net-Check" approach according to Schuh, Boos et al. (2009)

According to the objectives described in section 1.1, the benefits applying to manufacturing service providers and consumers were selected from an overall list of potentially relevant benefit categories. The selected benefit categories were rated, i.e. weighted and prioritised, by stakeholders using an ordinal scale ranging from 0 (no benefit) to 10 (most important strategic objective). The result of this selection and rating can be seen in table 8.6.

Benefit	Rating
Manufacturers	
Potential increase in sales	7
Access to additional market segments	5
Improved utilisation of existing resources	2
Consumers (end-customers and product designers)	
Utilisation of external competencies and resources	6

Table 8.6. Categories of benefits and their average rating per stakeholder group

Efforts which must be invested by manufacturing service providers and consumers to establish and use agile production networks were also taken from a generic list provided by Schuh, Boos et al. (2009). They were rated by stakeholders in the same way as benefits on a scale ranging from 0 (no efforts) to 10 (very high efforts) for both cases, participation in agile production networks without and with using the developed method and system aiding related activities. Table 8.7 shows the result of this rating of efforts to be invested. It can be seen that especially the efforts for common documentation and design guidelines, standardisation and transparency of cooperation processes, and the selection and alignment of partners could be reduced considerably by applying the developed method and system.

Efforts to be invested	Rating without method and system	Rating with method and system
Manufacturers		
Know-how management and protection	1	4
Common documentation and design guidelines	4	1
Standardisation and transparency of cooperation processes	5	1
Installation and usage of IT infrastructure and tools	6	4
Standardisation and modularisation of products / offered services	3	3
Consumers (end-customers and product designers)		
Coordination of overall activities	7	5
Selection and alignment of partners	6	2
Overall cost controlling	4	3

Table 8.7. Categories of efforts to be invested by different stakeholder groups and their average rating

To assess the relevance of effort reductions achieved by the method and system for the stakeholders' objectives, the impact of each effort category on the benefits was evaluated. From a manufacturer's perspective, the standardisation and transparency of cooperation processes was identified to be most relevant for increasing sales by entering additional markets and improving the utilisation of resources through participation in agile production networks. For manufacturing service consumers, the selection and alignment of partners contributes most to accessing external competencies and resources, which is also aided by common documentation and design guidelines, if provided and followed by manufacturers.

This means that the efforts required to participate in agile production networks are reduced for both, manufacturers and consumers, by applying the developed method and system, thus proving that the developments described in this thesis contribute to the achievement of overall business objectives of the stakeholders and are valuable for industrial application. While applying the method and system, according to section 7.3.3, it has to be considered that the degree to which the business objectives can be achieved depends on the overall reliability of the method and system, which is determined by the size of knowledge base, i.e. the number of previously configured products and agile production networks.

8.5. Evaluation Summary and Conclusion

Based on the execution of the application case, not only were the technical functionalities of the developments assessed, but also the achievement of business benefits stated in section 2.3.4. It has been demonstrated that the developed method for the personalised configuration and combination of manufacturing services is applicable in practice, and that it contributes to reducing the know-how and efforts required to configure agile production networks.

In this context, although the ability to individualise products is given in principle, it depends on the capability of the specific manufacturing services to be personalised. For example, when it comes to organic semiconductor products, i.e. OLED and OPV elements, masks must be prepared for each specific shape, resulting in high efforts and costs for total customisation. Accordingly, manufacturing technologies providing a high individualisation capability, such as stamp matrix sheet forming (Simon, Zitzlsberger et al. 2014), incremental sheet forming (Emmens, Sebastiani et al. 2010), or additive manufacturing technologies (Guo and Leu 2013), are promising candidates for integration into agile production networks.

The efforts to model manufacturing services as they occur for manufacturers are regarded as applicable for the chosen levels of detail, provided that the manufacturing services will be integrated into multiple agile production networks, which requires a respective platform reach. This, together with the result of the "Net-Check" approach, which confirms the reduction of efforts, especially of such for common documentation and design guidelines as well as standardisation and transparency of cooperation processes, approves that it can be beneficial for manufacturers to provide their services to agile production networks. Furthermore, the efforts and know-how required to select and align appropriate partners, which also includes the specification of products and their components, were proven to be reduced by applying the developed solution. This means, that the barriers for consumers of manufacturing services could be lowered.

By applying this business context while validating the method, model structures and functionalities of the IT system, there were 3 conditions identified, for which the application of the developed solution has the most potential. Considering the know-how required from manufacturing service consumers, the reliability of assessment results, i.e. recommendations and warnings (see section 7.3.3), and effort involved in modelling manufacturing services as provider, this is the case

- for configuring agile production networks for complex products or processes, since the greatest efforts and know-how are needed for these when identifying, establishing, and verifying links, application context settings, and parameter restrictions.

- if numerous product specifications and related agile production network configurations, i.e. manufacturing service combinations, are available in the knowledge base, since these are necessary to ensure the quality of assessment results. A high number of participants contributing to the platform as manufacturing service providers or customers would facilitate this.

- if manufacturing processes which are linked via dependencies are provided by flexible production facilities with a high degree of automation, since these have clearly defined ranges for customisation options and support the automated implementation of individual product specifications.

These overall evaluation results have been summarised in table 8.8 by comparing them with the overall objectives of the method listed in chapter 3.

Objective	Achievement
`Obj01`: Support personalisation of products	Achieved through parameterising manufacturing services and customer-specific manufacturing service configuration and combination.
`Obj02`: Manufacturability assessment	Achieved by dependency assessment mechanisms. However, the quality attained depends on the extent of the knowledge base.
`Obj03`: Reduction of know-how and efforts involved in the configuration and combination of manufacturing services	Achieved by dependency assessment mechanisms. However, the degree of their usefulness depends on the extent of the knowledge base.

Table 8.8. Achievement of method objectives

9. Conclusion and Outlook

To remain competitive, European manufacturing enterprises are increasingly focusing on their core business and processes, as well as on personalising their products. Together with an increasing product complexity, these trends lead to the need to configure production networks ad-hoc according to customer-specific product designs. When implementing concepts and methods to address this demand, appropriate IT systems must be applied to ensure their efficiency and benefits for the parties involved.

Product customisation tends to move forward from configurations based on predefined options towards personalisation which is not restricted by product engineering, but only by the available capabilities and capacities of manufacturing resources. These manufacturing capabilities need to be shared with and supplied to potential customers or product designers. To achieve this, service orientation is established in manufacturing, resulting in the provision of manufacturing services representing product components or process steps, which can be combined to form agile production networks. In the past, production networks have invariably been established in the long term. However, to support total customisation, more flexible concepts are required. Their implementation must allow manufacturing services to be substituted by others, or production networks to be configured ad-hoc according to customer-specific orders. Several methods and IT systems exist which support specific tasks when configuring agile production networks, such as the flexible configuration of manufacturing resources, communication among production network partners, and product configuration. However, up till now there has been no integrated solution which allows customers to seamlessly configure individual products and related production networks. To solve this problem, the aspects of the manufacturing system, production network, and customisation need to be integrated. Furthermore, it is necessary to reduce the efforts and know-how required to individually configure products and production networks in order to enable end-customers and product designers without extensive manufacturing expertise to utilise manufacturing services. Both can be achieved by providing a method and system for individually configuring and combining manufacturing services.

In order to develop this method and system, the requirements of the involved parties, i.e. manufacturing service providers and customers or product designers, have been analysed and put into a general context. These requirements cover the description and provision of manufacturing services, their selection and connection, as well as the assessment of manufacturing service configurations and combinations based on knowledge gained from previously defined agile production networks. Besides functional requirements, industrial success criteria such as compatibility with existing standards or IT security were also considered in order to ensure efficient application and acceptance of the developments in practice.

Existing solutions from research and standardisation have been evaluated regarding the fulfilment of the gathered requirements in order to identify gaps that need to be bridged. In doing so, appropriate research fields have been explored in detail. These include the modelling of manufacturing capabilities, their parameterisation and categorisation, the orchestration of services and configuration of manufacturing workflows, as well as existing knowledge-based approaches to support these activities. Furthermore, the ability of overall solutions to manage agile production networks has been analysed. As a result, no solution, i.e. method and IT system, could be identified which completely covers the specified requirements, since existing solutions either focus on the creation of static supply chains or are limited to a subset of tasks conducted during agile production network configuration. The basic need for research was identified to be a method for guiding agile production network participants through the configuration process, supported by appropriate information models representing manufacturing services and their connections, as well as by IT functionalities ensuring the manufacturability of the generated configurations.

To address these research gaps, the defined method for configuring and combining manufacturing services for personalised production provides guidance for manufacturing service providers and consumers, i.e. customers or product designers. It describes how to use the related model and system to share manufacturing services with potential customers, and reduce the efforts and know-how required to configure agile production networks. This includes the consideration of strategic objectives in order to decide about participation in a respective platform, the generation of manufacturing service and dependency models, their utilisation to assist end-customers and product designers, as well as the assessment of the feasibility and manufacturability of created product and production network configurations. Furthermore, the knowledge base and related dependency assessment mechanisms are improved incrementally while the solution is used, thus contributing to the sustained and successful application of the method.

The software system, which has been implemented as a tool aiding the execution of the method, consists of a data model for manufacturing services and IT functionalities for assessing combinations of manufacturing services. According to the requirements, the model represents all manufacturing service properties needed when configuring and combining manufacturing services. This includes related product and process characteristics and their customisation options, as well as information about the availability of capacities and contractual conditions, which are needed to integrate the manufacturing services into production networks. Additionally, dependencies between manufacturing services, which are established when configuring agile production networks, have been modelled. These represent the structure of the related manufacturing service trees, define the application context of certain manufacturing services, i.e. pre- or postconditions for their execution, by means of related product or process categories, and specify restrictions which may apply to manufacturing service parameters and their customisation options. During the process of individually configuring and combining manufacturing services, suggestions for improving dependencies are generated by analysing previously defined dependencies which are stored in a common knowledge base. Three major assessment steps are taken to do this: First, the compatibility of combined manufacturing services is checked by analysing their application context, i.e. relationships between respective product or process categories. Then, the results are detailed by considering related manufacturing service properties. Finally, all parameter restrictions, i.e. the effects which the adjustment of certain parameters has on the value or applicable range of other parameters, are verified throughout the established manufacturing service combination. These assessment steps enable recommendations or warnings regarding the configuration and combination of manufacturing services to be given to the system users, including indications of their prioritisation and reliability. Altogether, the developed IT system consisting of data models and algorithms, enables to efficiently execute the method to configure agile production networks.

In addition to testing the functionalities of the overall solution, i.e. method, model, and IT system, the achievement of its business objectives has been validated by applying it in the context of an application case from the organic semiconductor industry. In doing so, the applicability of the solution in practice was evaluated by rating relevant benefits and efforts to be invested by manufacturing service providers and consumers when participating in agile production networks. Especially the efforts for common documentation and design guidelines, standardisation and transparency of cooperation processes which need to be invested by manufacturers, as well as efforts and know-how required for the selection and alignment of partners by manufacturing service consumers could be reduced by the developed solution. At the same time, these efforts are contributing most to the objectives to potentially increase sales for manufacturers, and utilise external competencies and resources for manufacturing service consumers. This confirms that the developed method, model, and system contribute to the achievement of overall business objectives of the stakeholders and are valuable for industrial application. Furthermore, the solution turned out to be beneficial especially for configuring complex products, if utilising flexible automated manufacturing systems in the context of agile production networks, and if numerous pre-defined configurations are available in the knowledge base.

In addition to the results of the work described in this thesis, which proved that the developed method, model, and system can contribute to reducing the efforts and know-how required to configure agile production networks for personalised products, these developments have the potential to serve as basis for further improvements and research.

Reasoning results achieved during dependency assessment could be further improved, which could also contribute to improving efficiency when configuring agile production networks. To do so, further tools and algorithms need to be included to the dependency assessment. For instance, simulations could evaluate the impact of certain dependencies and configurations in more detail, and further AI methods and tools could increase the correctness of ontologies and related inferences by justifying reasoning results, remembering results from previous reasoning steps, or recognising inconsistencies in the knowledge base.

In the process of preparing the IT system for industrial application, further improvements are required regarding its security mechanisms, responsiveness, and usability, i.e. the intuitivity of user interaction. Furthermore, the complexity arising and efforts incurred when executing modelling tasks could be reduced by integrating the system more closely into related external IT tools for graphical product design. Up till now, this integration has been implemented through transferring specific parameter values unidirectionally to the manufacturing service models. If this is extended by automated data extraction and the feedback of verification results from and to the product design, the intuitive usage and efficiency of manufacturing service configuration could be improved.

In the same way, the efficiency of generating manufacturing service descriptions could be increased by adding an interface to automatically extract capabilities and capacities from the respective production IT systems. Vice versa, orders and related specific manufacturing service configurations would have to be fed back to these systems (semi-) automatically. Thus, to fully exploit the potential of the developed solution, it would have to be integrated into an overall management tool for agile production networks, which covers all operations, from the description of manufacturing services to the execution of orders.

Appendix

A. Manufacturing Service Models

This appendix describes the knowledge about single manufacturing services which was modelled in the context of the application case. In doing so, relevant product and process parameters have been identified, and their customization options and ranges, as well as their impact on each other have been analysed. The results of this modelling work can be seen in tables A.1, A.2 and A.3.

Parameter Category	Parameter	Internal Dependencies	Values
Geometry	[1] Part Length		300mm $\leq p_1 \leq$ 1200mm
	[2] Part Width		290mm $\leq p_2 \leq$ 330mm
	[3] Part Area	$p_3 = p_1 \cdot p_2$	
	[4] $\text{Border}_{\text{Length}}$		10mm $\leq p_4 \leq$ 30mm
	[5] $\text{Border}_{\text{Width}}$		10mm $\leq p_5 \leq$ 30mm
	[6] Cell Width		15mm
	[7] Active Width	$p_7 = n \cdot p_6;\ n \in \mathbb{N}$ $p_7 = p_2 - 2 \cdot p_5$	
	[8] Active Length	$p_8 = p_1 - 2 \cdot p_4$	
	[9] Active Area	$p_9 = p_7 \cdot p_8$	
Mechanical	[10] Thickness		0.5mm
	[11] Substrate		foil
	[12] Weight	$p_7 = 0.7 \frac{kg}{m^2} \cdot p_3$	

Optical	[13] Transparency		{0;5;10;15;20}%
	[14] Colour		{blue; green}
Electrical	[15] Voltage	${p_{15}}^1 = f(\frac{p_7}{p_6}, p_{13}, p_{14})$	
	[16] Current	${p_{16}}^1 = f(p_6, p_7, p_8, p_{13}, p_{14})$	
	[17] Power	$p_{17} = p_{15} \cdot p_{16}$	
	[18] Efficiency	${p_{18}}^1 = f(p_{13}, p_{14})$	
SLA	[19] Price	${p_{19}}^1 = f(p_3, p_9, p_{13}, p_{14})$	
	[20] Process lead time		16 hours
	[21] Delivery date	${p_{21}}^1 = f(utilization^2, p_{20})$	
	[22] Warranty		3 years

Table A.1. Parameter details of an OPV manufacturing service

Parameter Category	Parameter	Internal Dependencies	Values
Geometry	[23] Part Length		{75;150}mm
	[24] Part Width		$50\text{mm} \leq p_{24} \leq 76\text{mm}$
	[25] Part Area	$p_{25} = p_{23} \cdot p_{24}$	
	[26] Active Length		$(p_{23} = 75\text{mm} \rightarrow p_{26} = 58.4\text{mm}) \wedge (p_{23} = 150\text{mm} \rightarrow p_{26} = 128.9\text{mm})$
	[27] Border Width		$5\text{mm} \leq p_{27} \leq 7.5\text{mm}$
	[28] Active Width	$p_{28} = p_{24} - 2 \cdot p_{27}$	
	[29] Active Area	$p_{29} = p_{26} \cdot p_{28}$	

[1]Simplified expression
[2]From other system

Mechanical	[30] Thickness		1.9mm
	[31] Substrate		glass
	[32] Weight	$p_{32} = 0.0035\frac{g}{mm^2} \cdot p_{25}$	
Electrical	[33] Voltage	$((p_{26} = 58.4mm) \rightarrow (p_{33} = 9V)) \wedge ((p_{26} = 128.9mm) \rightarrow (p_{33} = 10V))$	
	[34] Current	${p_{34}}^1 = f(p_{29}, p_{38})$	
	[35] Power	$p_{35} = p_{33} \cdot p_{34}$, equation 6.3	
	[36] Efficiency	$p_{36} = (p_{41} + p_{44})/p_{35}$	
Optical	[37] Transparency	$((p_{38} = (\text{“}green\text{”} \vee \text{“}blue\text{”})) \rightarrow (p_{37} \leq 10\%)) \wedge ((p_{38} \neq (\text{“}green\text{”} \vee \text{“}blue\text{”})) \rightarrow (p_{37} \leq 45\%))$	{0;5;10;20;30;45}%
	[38] Colour		{white; blue; green; orange}
	[39] Colour temperature front	${p_{39}}^1 = f(p_{38})$	$p_{39} \leq$ 3200K
	[40] Luminance front	${p_{40}}^1 = f(p_{26}, p_{28}, p_{38})$	
	[41] Luminous flux front	${p_{41}}^1 = f(p_{29}, p_{37}, p_{38})$	
	[42] Colour temperature rear	${p_{42}}^1 = f(p_{37}, p_{38})$	$p_{42} \leq$ 2400K
	[43] Luminance rear	${p_{43}}^1 = f(p_{26}, p_{28}, p_{37}, p_{38})$	
	[44] Luminous flux rear	${p_{44}}^1 = f(p_{29}, p_{37}, p_{38})$	

SLA	[45] Price	${p_{45}}^1 = f(p_{25}, p_{37}, p_{38})$	
	[46] Process lead time	${p_{46}}^1 = f(p_{37})$	
	[47] Delivery date	${p_{47}}^1 = f(utilization^2, p_{46})$	
	[48] Warranty		3 years

Table A.2. Parameter details of an OLED manufacturing service

Parameter Category	Parameter	Internal Dependencies	Values
Geometry	[49] Part Length		{94.6;142;284}mm
	[50] Part Width		{56.5;71;94;142}mm
	[51] Part Area	$p_{51} = p_{49} \cdot p_{50}$	
	[52] Active Length	${p_{52}}^1 = f(p_{49})$	{77.8;125;264}mm
	[53] Active Width	${p_{53}}^1 = f(p_{50})$	{39.3;53.8;76.8;125}mm
	[54] Active Area	$p_{54} = p_{52} \cdot p_{53}$	
Mechani-cal	[55] Thickness		1.5;1.7mm
	[56] Substrate		{glass; foil}
	[57] Weight	${p_{57}}^1 = f(p_{51}, p_{55}, p_{56})$	
Electrical	[58] Voltage		10.5V
	[59] Current	${p_{59}}^1 = f(p_{54})$	
	[60] Power	$p_{60} = p_{58} \cdot p_{59}$	
	[61] Efficiency	$p_{61} = p_{66}/p_{60}$	

Optical	[62] Transparency		0%
	[63] Colour		white
	[64] Colour temperature		{2800;4000}K
	[65] Luminance		$3000\frac{cd}{m^2}$
	[66] Luminous flux	${p_{66}}^1 = f(p_{54}, p_{64})$	
SLA	[67] Price	${p_{67}}^1 = f(p_{49}, p_{56}, p_{53})$	
	[68] Process lead time		14 hours
	[69] Delivery date	${p_{69}}^1 = f(utilization^2, p_{68})$	
	[70] Warranty		3 years

Table A.3. Parameter details of a second OLED manufacturing service

In addition to these independent manufacturing services, table A.4 shows the model of a facade module which is assembled from the results of other manufacturing services such as the three described above. This includes parameter dependencies across manufacturing services, i.e. between the components and the final assembly process and related product.

Parameter Category	Parameter	Internal Dependencies	Values
Assembly	[71] No of areas on module		$[1;n]; n \in \mathbb{N}$
Assembly / Area template[3]	[72] Type of elements in area		OPV, OLED, Glass
	[73] Reference to element instance		Identifier of existing manufacturing service instance, including specification parameters
	[74] No of elements vertical		$[1;n]; n \in \mathbb{N}$
	[75] Distance of elements vertical		$5\text{mm} \leq p_{60}$
	[76] No of elements horizontal		$[1;n]; n \in \mathbb{N}$
	[77] Distance of elements horizontal		$5\text{mm} \leq p_{62}$
	[78] Orientation of elements		0;90°
	[79] Area Length	${p_{79}}^1 = f(p_{73}, p_{74}, p_{75}, p_{78})$	$400\text{mm} \leq p_{79} \leq 1600\text{mm}$
	[80] Area Width	${p_{80}}^1 = f(p_{73}, p_{76}, p_{77}, p_{78})$	$400\text{mm} \leq p_{80} \leq 1000\text{mm}$
	[81] Vertical position of area	${p_{81}}^4 = f(p_{71}, {p_{79}}^3, {p_{81}}^3, {p_{82}}^3)$	$0\text{mm} \leq p_{81} \leq 1200\text{mm}$
	[82] Horizontal position of area	${p_{82}}^4 = f(p_{71}, {p_{80}}^3, {p_{81}}^3, {p_{82}}^3)$	$0\text{mm} \leq p_{82} \leq 600\text{mm}$

[3]instantiated for all of the p_{71} areas during configuration of the particular customised product
[4]Verification against other areas to prevent overlaps, simplified expression

Installation	[83] Top Margin		50mm
	[84] Bottom Margin		50mm
	[85] Frame width		30mm $\leq p_{85} \leq$ 70mm
	[86] Junction box position		{top;bottom}, {right;left}
Geometry	[87] Module length	${p_{87}}^1 = f({p_{79}}^3, {p_{81}}^3, p_{83}, p_{84})$	500mm $\leq p_{87}$ $\leq$ 1840mm
	[88] Module width	${p_{88}}^1 = f({p_{80}}^3, {p_{82}}^3)$	400mm $\leq p_{88}$ $\leq$ 1000mm
Mechanical	[89] Thickness	$p_{89} = f({p_{73}}^3)$	10mm $\leq p_{89} \leq$ 16mm
	[90] Weight	${p_{90}}^1 = f(p_{87}, p_{88}, p_{89}, {p_{73}}^3, {p_{74}}^3, {p_{76}}^3)$	
Electrical	[91] Voltage in	${p_{91}}^1 = f(p_{71}, {p_{72}}^3, {p_{73}}^3, {p_{74}}^3, {p_{76}}^3)$	
	[92] Current in	${p_{92}}^1 = f(p_{71}, {p_{72}}^3, {p_{73}}^3, {p_{74}}^3, {p_{76}}^3)$	
	[93] Power in	$p_{93} = p_{91} \cdot p_{92}$	
	[94] Voltage out	${p_{94}}^1 = f(p_{71}, {p_{72}}^3, {p_{73}}^3, {p_{74}}^3, {p_{76}}^3)$	
	[95] Current out	${p_{95}}^1 = f(p_{71}, {p_{72}}^3, {p_{73}}^3, {p_{74}}^3, {p_{76}}^3)$	
	[96] Power out	$p_{96} = p_{94} \cdot p_{95}$	
SLA	[97] Price	${p_{97}}^1 = f(p_{71}, {p_{73}}^3, {p_{74}}^3, {p_{76}}^3)$	
	[98] Process lead time	${p_{98}}^1 = f(p_{71}, {p_{74}}^3, {p_{76}}^3, p_{87}, p_{88})$	
	[99] Delivery date	${p_{99}}^1 = f(p_{71}, {p_{73}}^3, p_{98}, utilization^2)$	
	[100] Warranty		3 years

Table A.4. Parameter details of a lamination and framing manufacturing service

B. Modelled Categories and Application Context

To complete the models of the manufacturing services, related products and processes have been categorised. In doing so, eCl@ss has been applied before further detailing the categories with custom definitions. Figures B.1 and B.2 show an excerpt of the category trees for products and processes which resulted from that.

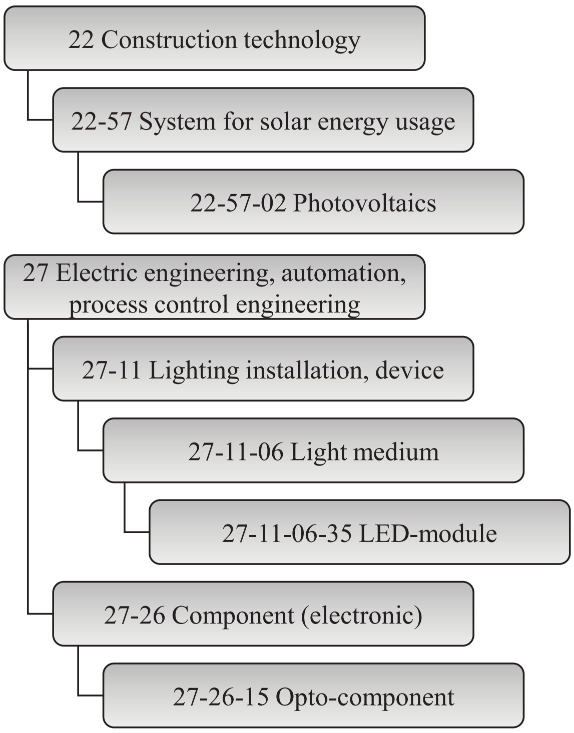

Figure B.1. Product categories from eCl@ss used in the context of the application example

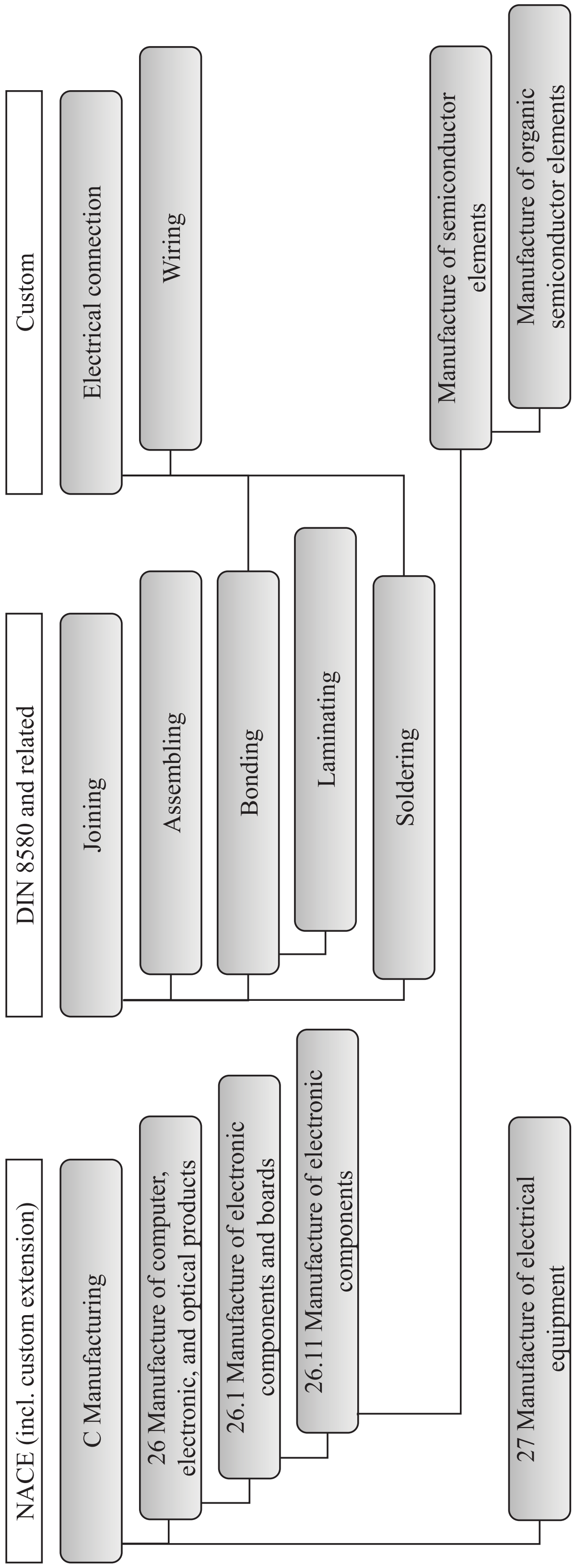

Figure B.2. Process categories modelled in the context of the application example

These categories provide the basis for the application context of the manufacturing services which are modelled as described in appendix A. Accordingly, table B.1 shows the application context rules applied which are used to assess dependencies established in the context of the application case.

Source Service Category	Application Context Type	Sink Service Category
Manufacture of organic semiconductor element	precondition	Glass (for OLED process 1, specialisation of substrate)
Manufacture of organic semiconductor element	precondition	Foil (for OPV process, specialisation of substrate)
Manufacture of organic semiconductor element	precondition	Substrate (for OLED process 2)
Component (electronic)	postcondition	Electrical connection (wiring/bonding/soldering)
Manufacture of organic semiconductor element	postcondition	Joining (lamination)
Lamination	precondition	Substrate
Lamination	precondition	Opto-component (organic semiconductor)
Lamination	postcondition	Assembly (framing)

Table B.1. Modelled application context conditions

Bibliography

Afsarmanesh and Camarinha-Matos (2005) Afsarmanesh, Hamideh and Camarinha-Matos, Luis M., 2005, A Framework for Management of Virtual Organization Breeding Environments, In: Camarinha-Matos, Luis M., Afsarmanesh, Hamideh, and Ortiz, Angel (eds.), *Collaborative Networks and Their Breeding Environments*, New York: Springer, *IFIP — The International Federation for Information Processing*, vol. 186, pp. 35–48, ISBN 9780387282596, doi:10.1007/0-387-29360-4_4

Akbarzadeh and Pasek (2008) Akbarzadeh, Nasim and Pasek, Zbigniew J., 2008, An analytical model for manufacturing service supply contracts, *Journal of Manufacturing Systems* **vol. 27**(2) pp. 70–76, doi:10.1016/j.jmsy.2008.11.003

Ameri and McArthur (2013) Ameri, Farhad and McArthur, Christian, 2013, A multi-agent system for autonomous supply chain configuration, *The International Journal of Advanced Manufacturing Technology* **vol. 66**(5–8) pp. 1097–1112, doi:10.1007/s00170-012-4392-9

Ameri and Patil (2012) Ameri, Farhad and Patil, Lalit, 2012, Digital manufacturing market: a semantic web-based framework for agile supply chain deployment, *Journal of Intelligent Manufacturing* **vol. 23**(5) pp. 1817–1832, doi:10.1007/s10845-010-0495-z

Ameri, Urbanovsky et al. (2012) Ameri, Farhad, Urbanovsky, Colin, and McArthur, Christian, 2012, A Systematic Approach to Developing Ontologies for Manufacturing Service Modeling, In: Anastasiou, Dimitra, Ramos, Luis, Krima, Sylvere, and Chen, Yuh-Jen (eds.), *Proceedings of the Second Workshop on Ontology and Semantic Web for Manufacturing (OSEMA 2012), Graz, Austria, July 24, 2012*, CEUR Workshop Proceedings, vol. 886, pp. 1–14, URL `http://ceur-ws.org/Vol-886/` (2015-08-26)

Anderl and Trippner (2000) Anderl, Reiner and Trippner, Dietmar, 2000, *STEP Standard for the Exchange of Product Model Data: Eine Einführung in die Entwicklung, Implementierung und industrielle Nutzung der Normenreihe ISO 10303 (STEP)*, Stuttgart: B. G. Teubner, ISBN 3519063778

Angles (2012) Angles, Renzo, 2012, A Comparison of Current Graph Database Models, In: *2012 IEEE 28th International Conference on Data Engineering Workshops (ICDEW)*, Piscataway: IEEE, pp. 171–177, doi:10.1109/ICDEW.2012.31

Argote (2013) Argote, Linda, 2013, *Organizational Learning: Creating, Retaining and Transferring Knowledge*, New York: Springer, 2nd ed., ISBN 9781461452508

Azouzi, D'Amours et al. (2010) Azouzi, Riadh, D'Amours, Sophie, and Beauregard, Robert, 2010, An Agility Reference Model for the Manufacturing Enterprise: The Example of the Furniture Industry, In: Piller, Frank T. and Tseng, Mitchell M. (eds.), *Handbook of Research in Mass Customization and Personalization*, New Jersey: World Scientific, pp. 403–426, ISBN 9814280283

Bakos (1991) Bakos, J. Yannis, 1991, Information Links and Electronic Marketplaces: The Role of Interorganizational Information Systems in Vertical Markets, *Journal of Management Information Systems* **vol. 8**(2) pp. 31–52

Barros, Oberle et al. (2012) Barros, Alistair, Oberle, Daniel, Kylau, Uwe, and Heinzl, Steffen, 2012, Design Overview of USDL, In: Barros, Alistair and Oberle, Daniel (eds.), *Handbook of Service Description: USDL and Its Methods*, New York: Springer, pp. 187–225, ISBN 9781461418634

Bengel (2010) Bengel, Matthias, 2010, *Workpiece-centered approach to reconfiguration in manufacturing engineering*, *ISW/IPA Forschung und Praxis*, vol. 175, Heimsheim: Jost-Jetter, ISBN 9783939890607, Stuttgart, University, Ph.D. thesis, 2010

Bengtsson (2001) Bengtsson, Jens, 2001, Manufacturing flexibility and real options: A review, *International Journal of Production Economics* **vol. 74**(1–3) pp. 213–224, doi:10.1016/S0925-5273(01)00128-1

Berger, Mangold et al. (2009) Berger, Stefan, Mangold, Christoph, Meyer, Sebastian, Westkämper, Engelbert, and Zahn, Erich, 2009, Das Stuttgarter Unternehmensmodell in der Theorie: Wissen im Kontext der Wandlungsfähigkeit, In: Westkämper, Engelbert and Zahn, Erich (eds.), *Wandlungsfähige Produktionsunternehmen: Das Stuttgarter Unternehmensmodell*, Berlin: Springer, pp. 186–201, ISBN 9783540218890, doi:10.1007/978-3-540-68890-7_5

Blecker, Friedrich et al. (2005) Blecker, Thorsten, Friedrich, Gerhard, Kaluza, Bernd, Abdelkafi, Nizar, and Kreutler, Gerold, 2005, *Information and Management Systems for Product Customization*, *Integrated series in information systems*, vol. 7, New York: Springer, ISBN 9780387233482

Boley, Paschke et al. (2016) Boley, Harold, Paschke, Adrian, Athan, Tara, Giurca, Adrian, Bassiliades, Nick, Governatori, Guido, Palmirani, Monica, Wyner, Adam, Kozlenkov, Alexander, and Zou, Gen (eds.), 2016, Specification of RuleML 1.02, URL `http://wiki.ruleml.org/index.php/Specification_of_RuleML_1.02` (2016-02-22)

Bosak, McGrath et al. (2013) Bosak, Jon, McGrath, Tim, and Holman, G. Ken (eds.), 2013, Universal Business Language Version 2.1, OASIS, URL `http://docs.oasis-open.org/ubl/os-UBL-2.0-update/os-UBL-2.0-update.pdf` (2015-05-15)

Boyd, Noller et al. (2008) Boyd, Alan, Noller, David, Peters, Paul, Salkeld, Dave, Thomasma, Tim, Gifford, Charlie, Pike, Steven, and Smith, Alison, 2008, SOA in Manufacturing Guidebook: A MESA International, IBM Corporation and Capgemini co-branded white paper, MESA, URL ftp://public.dhe.ibm.com/software/plm/pdif/MESA_SOAinManufacturingGuidebook.pdf (2016-09-29)

Boyer, Gao et al. (2011) Boyer, John, Gao, Sandy, Malaika, Susan, Maximilien, Michael, Salz, Rich, and Simeon, Jerome, 2011, Experiences with JSON and XML Transformations: IBM Submission to W3C Workshop on Data and Services Integration. October 20-21 2011, Bedford, MA, USA, URL https://www.w3.org/2011/10/integration-workshop/p/XML_JSON_mapping_paper.pdf (2016-02-09)

Bray, Paoli et al. (2006) Bray, Tim, Paoli, Jean, Sperberg-McQueen, C. M., Maler, Eve, Yergeau, François, and Cowan, John (eds.), 2006, Extensible Markup Language (XML) 1.1, W3C, URL https://www.w3.org/TR/2006/REC-xml11-20060816/ (2015-05-12)

Brutzman and Daly (2007) Brutzman, Don and Daly, Leonard, 2007, *X3D: Extensible 3D Graphics for Web Authors*, Series in interactive 3D technology, San Francisco: Morgan Kaufmann, ISBN 9780120885008

Burghardt, Zimmermann et al. (2007)
Burghardt, Thomas, Zimmermann, Matthias, and Jähn, Hendrik, 2007, Eine Serviceorientierte Architektur (SOA) als Basis zur informationstechnischen Vernetzung von KMU in

auftragsbezogenen Produktionsnetzen am Beispiel des Betreiberkonzeptes Extended Value Chain Management (EVCM), In: Meißner, Klaus and Engelien, Martin (eds.), *Virtuelle Organisation und Neue Medien 2007: Workshop GeNeMe 2007 - Gemeinschaften in Neuen Medien*, Dresden: TUDpress, pp. 239–250, ISBN 9783940046369

Cai, Zhang et al. (2011) Cai, Ming, Zhang, William. Y., and Zhang, Kai, 2011, ManuHub: A Semantic Web System for Ontology-Based Service Management in Distributed Manufacturing Environments, *IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans* **vol. 41**(3) pp. 574–582, doi:10.1109/TSMCA.2010.2076395

Cao and Dowlatshahi (2005) Cao, Qing and Dowlatshahi, Shad, 2005, The impact of alignment between virtual enterprise and information technology on business performance in an agile manufacturing environment, *Journal of Operations Management* **vol. 23**(5) pp. 531–550, doi:10.1016/j.jom.2004.10.010

Daum (2007) Daum, Berthold, 2007, *Java 6: Programmieren mit der Java Standard Edition*, Programmer's choice, München: Addison-Wesley, ISBN 9783827324689

Delen and Sharda (2008) Delen, Dursun and Sharda, Ramesh, 2008, Artificial Neural Networks in Decision Support Systems, In: Burstein, Frada and Holsapple, Clyde W. (eds.), *Handbook on Decision Support Systems 1*, Berlin: Springer, International

Handbooks on Information Systems, pp. 557–580, ISBN 9783540487135, doi:10.1007/978-3-540-48713-5_26

DIN 8580:2003-09 (2003) DIN, Deutsches Institut für Normung, DIN 8580:2003-09, 2003, Fertigungsverfahren - Begriffe, Einteilung, Berlin: Beuth

Dotoli and Falagario (2012) Dotoli, Mariagrazia and Falagario, Marco, 2012, A Hierarchical Model for Optimal Supplier Selection in Multiple Sourcing Contexts, *International Journal of Production Research* **vol. 50**(11) pp. 2953–2967, doi:10.1080/00207543.2011.578167

D'Souza and Williams (2000) D'Souza, Derrick E. and Williams, Fredrik P., 2000, Toward a taxonomy of manufacturing flexibility dimensions, *Journal of Operations Management* **vol. 18**(5) pp. 577–593, doi:10.1016/S0272-6963(00)00036-X

Dulmet, Lhote et al. (2002) Dulmet, Maryvonne, Lhote, François, and Bonjour, Eric, 2002, Resources Characterisation in Manufacturing Systems, In: *2002 IEEE International Conference on Systems, Man and Cybernetics (SMC)*, Piscataway: IEEE, doi:10.1109/ICSMC.2002.1176447

Emmens, Sebastiani et al. (2010) Emmens, Wilko C., Sebastiani, Gerd, and van den Boogaard, Ton A.H., 2010, The technology of Incremental Sheet Forming—A brief review of the history, *Journal of Materials Processing Technology* **vol. 210**(8) pp. 981–997, doi:10.1016/j.jmatprotec.2010.02.014

European Commission (2013) European Commission, Directorate-General for Research and Innovation, 2013, *Factories of the Future: Multi-annual roadmap for the contractual PPP under Horizon 2020*, Luxembourg: Publications Office of the European Union, ISBN 9789279312380

European Commission (2014) European Commission, Eurostat, 2014, *Key figures on Europe: 2014 edition*, eurostat Pocketbooks, Luxembourg: Publications Office of the European Union, ISBN 9789279344299

Eyers and Dotchev (2010) Eyers, Daniel and Dotchev, Krassimir, 2010, Technology review for mass customisation using rapid manufacturing, *Assembly Automation* **vol. 30**(1) pp. 39–46, doi:10.1108/01445151011016055

Fallside and Walmsley (2004) Fallside, David C. and Walmsley, Priscilla (eds.), 2004, XML Schema Part 0: Primer, W3C, URL `https://www.w3.org/TR/2004/REC-xmlschema-0-20041028/` (2015-06-07)

Faucher, Everett et al. (2008) Faucher, Jean-Baptiste P. L., Everett, André M., and Lawson, Rob, 2008, What Do We Know About Knowledge?, In: Koohang, Alex, Harman, Keith, and Britz, Johannes (eds.), *Knowledge Management: Theoretical foundations*, Santa Rosa: Informing Science Press, pp. 41–78, ISBN 9781932886061

Felfernig, Hotz et al. (2014) Felfernig, Alexander, Hotz, Lothar, Bagley, Claire, and Tiihonen, Juha (eds.), 2014, *Knowledge-Based Configuration: From Re-*

search to Business Cases, Waltham: Morgan Kaufmann, ISBN 9780124158177

Ferreira, Sarraipa et al. (2014) Ferreira, Jose, Sarraipa, Joao, Agostinho, Carlos, Gigante, Fernando, Nunez, Maria Jose, and Jardim-Goncalves, Ricardo, 2014, Collaborative production using dynamic manufacturing networks for SME's, In: Terzi, Sergio (ed.), *International ICE Conference on Engineering, Technology and Innovation (ICE), 2014*, Piscataway: IEEE, ISBN 9781479947355, doi:10.1109/ICE.2014.6871620

Fogliatto, da Silveira et al. (2012) Fogliatto, Flavio S., da Silveira, Giovani J.C., and Borenstein, Denis, 2012, The mass customization decade: An updated review of the literature, *International Journal of Production Economics* **vol. 138**(1) pp. 14–25, doi:10.1016/j.ijpe.2012.03.002

Giess, McMahon et al. (2009) Giess, Matt D., McMahon, Chris A., Booker, Julian D., and Stewart, David, 2009, Application of faceted classification in the support of manufacturing process selection, *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* **vol. 223**(6) pp. 597–608, doi:10.1243/09544054JEM1274

Göhner and Weyrich (2014) Göhner, Peter and Weyrich, Michael, 2014, Agent-Based Concepts for Manufacturing Automation, In: Müller, Jörg P., Weyrich, Michael, and Bazzan, Ana L. C. (eds.), *Multiagent System Technologies: Proceedings of the*

12th German Conference (MATES 2014), Stuttgart, Germany, September 23–25, 2014, Cham: Springer, *Lecture Notes in Computer Science*, vol. 8732, pp. 90–102, ISBN 9783319115849, doi: 10.1007/978-3-319-11584-9_7

Gosling, Naim et al. (2013) Gosling, Jonathan, Naim, Mohamed, and Towill, Denis, 2013, A supply chain flexibility framework for engineer-to-order systems, *Production Planning & Control* **vol. 24**(7) pp. 552–566, doi: 10.1080/09537287.2012.659843

Grenz and Pfadenhauer (2012) Grenz, Tilo and Pfadenhauer, Michaela, 2012, Kundenintegration vs. Kundenpartizipation. Wertschöpfungskonzepte mediatisierter Geschäftsmodelle, In: Dunkel, Wolfgang and Bienzeisler, Bernd (eds.), *3sResearch: Sozialwissenschaftliche Dienstleistungsforschung: Erste Tagung der Initiative Social Science Service Research (3sR), Tagungsband, München, 26.-27.1.2012*, Stuttgart: Fraunhofer Verlag, ISBN 3839604060

Groover (2010) Groover, Mikell P., 2010, *Fundamentals of Modern Manufacturing: Materials, Processes, and Systems*, Hoboken: John Wiley & Sons, 4th ed., ISBN 9780470467008

Gunasekaran, Lai et al. (2008) Gunasekaran, Angappa, Lai, Kee-hung, and Cheng, T. C. Edwin, 2008, Responsive supply chain: A competitive strategy in a networked economy, *Omega* **vol. 36**(4) pp. 549–564, doi: 10.1016/j.omega.2006.12.002

Guo and Leu (2013) Guo, Nannan and Leu, Ming C., 2013, Additive manufacturing: technology, applications and research needs, *Frontiers of Mechanical Engineering* **vol. 8**(3) pp. 215–243, doi:10.1007/s11465-013-0248-8

Harnad (2005) Harnad, Stevan, 2005, To Cognize is to Categorize: Cognition is Categorization, In: Cohen, Henri and Lefebvre, Claire (eds.), *Handbook of categorization in cognitive science*, Oxford: Elsevier, pp. 19–43, ISBN 0080446124

Heinzl, Harnisch et al. (2006) Heinzl, Joachim, Harnisch, Jan, Irlinger, Franz, Hoffmann, Hartmut, Petry, Raphael, Stanchev, Stanislav, Zäh, Michael F., and Ulrich, Christopher, 2006, Technologien für die Fertigung individualisierter Produkte, In: Lindemann, Udo, Reichwald, Ralf, and Zäh, Michael F. (eds.), *Individualisierte Produkte: Komplexität beherrschen in Entwicklung und Produktion*, Berlin: Springer, VDI, pp. 89–113, ISBN 9783540255062

Hieu, Zlatov et al. (2005) Hieu, Le Chi, Zlatov, Nikolay, van der Sloten, Jos, Bohez, Erik L. J., Khanh, L., Binh, P. H., Oris, Philip, and Toshev, Yuli, 2005, Medical rapid prototyping applications and methods, *Assembly Automation* **vol. 25**(4) pp. 284–292, doi:10.1108/01445150510626415

Hitzler, Krötzsch et al. (2008) Hitzler, Pascal, Krötzsch, Markus, Rudolph, Sebastian, and Sure, York, 2008, *Semantic Web: Grundlagen*, EXamen.press, Berlin: Springer, ISBN 3540339949

Hoffmeister (2013) Hoffmeister, Michael, 2013, *Modelle zur aufgabengeführten Produktionsausführung in der wandlungsfähigen Produktion*, *Stuttgarter Beiträge zur Produktionsforschung*, vol. 8, Stuttgart: Fraunhofer Verlag, ISBN 9783839605301, Stuttgart, University, Ph.D. thesis, 2012

Hohpe and Woolf (2012) Hohpe, Gregor and Woolf, Bobby, 2012, *Enterprise Integration patterns: Designing, Building, and Deploying Messaging Solutions*, Addison-Wesley Signature Series, Boston: Addison-Wesley, 16th ed., ISBN 9780321200686

Hopp and Spearman (2011) Hopp, Wallace J. and Spearman, Mark L., 2011, *Factory Physics*, Long Grove: Waveland Press, 3rd ed., ISBN 9781577667391

Hotz, Felfernig et al. (2014) Hotz, Lothar, Felfernig, Alexander, Stumptner, Markus, Ryabokon, Anna, Bagley, Claire, and Wolter, Katharina, 2014, Configuration Knowledge Representation and Reasoning, In: Felfernig, Alexander, Hotz, Lothar, Bagley, Claire, and Tiihonen, Juha (eds.), *Knowledge-Based Configuration: From Research to Business Cases*, Waltham: Morgan Kaufmann, pp. 41–72, ISBN 9780124158177

Hoyer (2014) Hoyer, Niclas, 2014, SPARQL and OWL 2 Inference for Neo4j, Research Group for Communication Systems, Department of Computer Science, CAU Kiel, URL `https://comsys.informatik.uni-kiel.de/lang/en/res/sparql-and-owl-2-inference-for-neo4j/` (2016-03-14)

Huspeninová and Homolka (2012)
Huspeninová, Kateřina and Homolka, Lubor, 2012, Virtual Enterprise: Benefits and its Quantification, In: Politis, John (ed.), *Proceedings of the 8th European Conference on Management, Leadership and Governance (ECMLG 2012)*, Reading: Academic Publishing International Limited, pp. 497–504, ISBN 9781908272768

IEC 61360-4:2005 DB (2005) IEC, International Electrotechnical Commission, IEC 61360-4:2005 DB, 2005, Standard data element types with associated classification scheme for electric components, URL `http://cdd.iec.ch/cdd/iec61360/iec61360.nsf` (2015-07-18)

IEC 62264-1:2013 (2013) IEC, International Electrotechnical Commission, IEC 62264-1:2013, 2013, Enterprise Control System Integration Part 1: Models and Terminology, Berlin: Beuth

Inman and Blumenfeld (2014) Inman, Robert R. and Blumenfeld, Dennis E., 2014, Product complexity and supply chain design, *International Journal of Production Research* **vol. 52**(7) pp. 1956–1969, doi:10.1080/00207543.2013.787495

ISO 14649-10:2004 (2004) ISO, International Organisation for Standardisation, ISO 14649-10:2004, 2004, Industrial automation systems and integration – Physical device control – Data model for computerized numerical controllers. Part 10: General process data

ISO 22745-1:2010 (2010) ISO, International Organisation for Standardisation, ISO 22745-1:2010, 2010, Industrial automation systems and integration – Open technical dictionaries and their application to master data

ISO/IEC 25010:2011 (2011) ISO, International Organisation for Standardisation / IEC, International Electrotechnical Commission, ISO/IEC 25010:2011, 2011, Systems and software engineering – Systems and software Quality Requirements and Evaluation (SQuaRE) – System and software quality models

Jang, Jeong et al. (2008) Jang, Jungho, Jeong, Buhwan, Kulvatunyou, Boonserm, Chang, Jaegyong, and Cho, Hyunbo, 2008, Discovering and integrating distributed manufacturing services with semantic manufacturing capability profiles, *International Journal of Computer Integrated Manufacturing* **vol. 21**(6) pp. 631–646, doi:10.1080/09511920701350920

Josuttis (2008) Josuttis, Nicolai, 2008, *SOA in der Praxis: System-Design für verteilte Geschäftsprozesse*, Heidelberg: dpunkt.verlag, ISBN 9783898644761

json.org (2006) json.org, 2006, JSON: The Fat-Free Alternative to XML, URL `http://www.json.org/xml.html` (2015-05-12)

Karaboga, Gorkemli et al. (2014)

Karaboga, Dervis, Gorkemli, Beyza, Ozturk, Celal, and Karaboga, Nurhan, 2014, A comprehensive survey: artificial bee colony (ABC) algorithm and applications, *Artificial Intelligence Review* **vol. 42**(1) pp. 21–57, doi:10.1007/s10462-012-9328-0

Keller and Ludwig (2003) Keller, Alexander and Ludwig, Heiko, 2003, The WSLA Framework: Specifying and Monitoring Service Level Agreements for Web Services, *Journal of Network and Systems Management* **vol. 11**(1) pp. 57–81, doi:10.1023/A:1022445108617

Kiemes, Novelli et al. (2012) Kiemes, Tom, Novelli, Francesco, and Oberle, Daniel, 2012, Service Pricing, In: Barros, Alistair and Oberle, Daniel (eds.), *Handbook of Service Description: USDL and Its Methods*, New York: Springer, pp. 227–242, ISBN 9781461418634, doi:10.1007/978-1-4614-1864-1_9

Kinkel (2012) Kinkel, Steffen, 2012, Trends in production relocation and backshoring activities: Changing patterns in the course of the global economic crisis, *International Journal of Operations & Production Management* **vol. 32**(6) pp. 696–720, doi:10.1108/01443571211230934

Kodzi and Gazo (2010) Kodzi, Emmanuel T. Jr. and Gazo, Rado, 2010, Operationalizing Mass Customization - A Conceptual Model Based on Recent Studies in Furniture Manufacturing, In: Piller, Frank T. and Tseng, Mitchell M. (eds.), *Handbook of Research in Mass Customization and Personalization*, New Jersey: World Scientific, pp. 79–96, ISBN 9814280283

Konrad (2012) Konrad, Konstantin, 2012, *Verfahren zum semantisch unterstützten Anlagenanlauf von Montagesystemen*, *Stuttgarter Beiträge zur Produktionsforschung*, vol. 5, Stuttgart: Fraunhofer Verlag, ISBN 3839604559, Stuttgart, University, Ph.D. thesis, 2012

Koren (2010) Koren, Yoram, 2010, *The Global Manufacturing Revolution: Product-Process-Business Integration and Reconfigurable Systems*, *Wiley series in systems engineering and management*, vol. 1, Hoboken: John Wiley & Sons, ISBN 9780470583777

Krampe and Lucke (2006) Krampe, Horst and Lucke, Hans-Joachim (eds.), 2006, *Grundlagen der Logistik: Theorie und Praxis logistischer Systeme*, München: Huss-Verlag, 3rd ed., ISBN 3937711236

Landherr (2014) Landherr, Martin H., 2014, *Integrierte Produkt- und Montagekonfiguration für die variantenreiche Serienfertigung*, *Stuttgarter Beiträge zur Produktionsforschung*, vol. 39, Stuttgart: Fraunhofer Verlag, ISBN 3839608090, Stuttgart, University, Ph.D. thesis, 2014

Lanza, Moser et al. (2011) Lanza, Gisela, Moser, Raphael, Scholz-Reiter, Bernd, Özsahin, Mehmet-Emin, Schuhkraft, Susanne, Meil, Pamela, and Rasp, Franziska, 2011, Planung und Optimierung wandlungsfähiger globaler Wertschöpfungsnetzwerke, *Industrie Management* **vol. 27**(3) pp. 57–60

Lanza, Moser et al. (2012) Lanza, Gisela, Moser, Raphael, and Ruhrmann, Stefan, 2012, Wandlungstreiber global agierender Produktionsunternehmen: Sammlung, Klassifikation und Quantifizierung, *wt Werkstattstechnik online* **vol. 102**(4) pp. 200–205

Lartigau, Xu et al. (2015) Lartigau, Jorick, Xu, Xiaofei, Nie, Lanshun, and Zhan, Dechen, 2015, Cloud manufacturing service composition based on QoS with geo-perspective transportation using an improved Artificial Bee Colony optimisation algorithm, *International Journal of Production Research* **vol. 53**(14) pp. 4380–4404, doi:10.1080/00207543.2015.1005765

Lemaignan, Siadat et al. (2006) Lemaignan, Séverin, Siadat, Ali, Dantan, Jean-Yves, and Semenenko, Anatoli, 2006, MASON: A Proposal For An Ontology Of Manufacturing Domain, In: Mařik, Vladimír (ed.), *IEEE Workshop on Distributed Intelligent Systems: Collective Intelligence and its Applications*, Piscataway: IEEE, pp. 195–200, ISBN 076952589X, doi:10.1109/DIS.2006.48

Lindemann and Maurer (2006) Lindemann, Udo and Maurer, Maik, 2006, Entwicklung und Strukturplanung individualisierter Produkte, In: Lindemann, Udo, Reichwald, Ralf, and Zäh, Michael F. (eds.), *Individualisierte Produkte: Komplexität beherrschen in Entwicklung und Produktion*, Berlin: Springer, VDI, pp. 41–87, ISBN 9783540255062

Lohse, Hirani et al. (2005) Lohse, Niels, Hirani, Hitendra, and Ratchev, Svetan, 2005, Equipment ontology for modular reconfigurable assembly systems, *International Journal of Flexible Manufacturing Sys-*

tems **vol. 17**(4) pp. 301–314, doi:10.1007/s10696-006-9030-0

Loskyll, Schlick et al. (2011) Loskyll, Matthias, Schlick, Jochen, Hodek, Stefan, Ollinger, Lisa, Gerber, Tobias, and Pirvu, Bogdan, 2011, Semantic service discovery and orchestration for manufacturing processes, In: Mammeri, Zoubir (ed.), *2011 IEEE 16th Conference on Emerging Technologies & Factory Automation (ETFA)*, Piscataway: IEEE, ISBN 9781457700187, doi:10.1109/ETFA.2011.6058988

Loukis and Charalabidis (2013) Loukis, Euripidis N. and Charalabidis, Yannis K., 2013, An empirical investigation of information systems interoperability business value in European firms, *Computers in Industry* **vol. 64**(4) pp. 412–420, doi:10.1016/j.compind.2013.01.005

Lu, Shao et al. (2014) Lu, Yuqian, Shao, Qun, Singh, Chirpreet, Xu, Xun, and Ye, Xinfeng, 2014, Ontology for manufacturing resources in a cloud environment, *International Journal of Manufacturing Research* **vol. 9**(4) pp. 448–469, doi:10.1504/IJMR.2014.066666

Ludewig and Lichter (2013) Ludewig, Jochen and Lichter, Horst, 2013, *Software Engineering: Grundlagen, Menschen, Prozesse, Techniken*, Heidelberg: dpunkt.verlag, 3rd ed., ISBN 9783864900921

MacKenzie, Laskey et al. (2006) MacKenzie, C. Matthew, Laskey, Ken, McCabe, Francis, Brown, Peter F., and Meth, Rebekah (eds.), 2006, Reference Model for

Service Oriented Architecture 1.0, OASIS, URL http://docs.oasis-open.org/soa-rm/v1.0/soa-rm.pdf (2015-06-18)

Malerba and Nelson (2011) — Malerba, Franco and Nelson, Richard, 2011, Learning and catching up in different sectoral systems: evidence from six industries, *Industrial and Corporate Change* **vol. 20**(6) pp. 1645–1675, doi:10.1093/icc/dtr062

Mandel (2012) — Mandel, Jörg, 2012, *Modell zur Gestaltung von Build-to-Order-Produktionsnetzwerken: Univ., Diss.–Stuttgart, 2011*, *Stuttgarter Beiträge zur Produktionsforschung*, vol. 2, Stuttgart: Fraunhofer Verlag, ISBN 3839604346, Stuttgart, University, Ph.D. thesis, 2012

Marienfeld, Höfig et al. (2012) — Marienfeld, Florian, Höfig, Edzard, Bezzi, Michele, Flügge, Matthias, Pattberg, Jonas, Serme, Gabriel, Brucker, Achim D., Robinson, Philip, Dawson, Stephen, and Theilmann, Wolfgang, 2012, Service Levels, Security, and Trust, In: Barros, Alistair and Oberle, Daniel (eds.), *Handbook of Service Description: USDL and Its Methods*, New York: Springer, pp. 295–326, ISBN 9781461418634, doi:10.1007/978-1-4614-1864-1_12

Markaki, Panopoulos et al. (2013)

Markaki, Ourania, Panopoulos, Dimitrios, Kokkinakos, Panagiotis, Koussouris, Sotirios, and Askounis, Dimitrios, 2013, Towards Adopting Dynamic Manufacturing Networks for Future Manufacturing: Benefits and Risks of the IMAGINE DMN End-to-End Management Methodology, In: Ley, Graham and Reddy, Sumitra (eds.), *2013 IEEE 22nd International Workshop on Enabling Technologies: Infrastructure for Collaborative Enterprises (WETICE)*, Piscataway: IEEE, pp. 305–310, ISBN 9780769550022, doi:10.1109/WETICE.2013.64

Matzner and Becker (2012) Matzner, Martin and Becker, Jörg, 2012, Requirements for a Service Description Language — Findings from a Delphi Study, In: Barros, Alistair and Oberle, Daniel (eds.), *Handbook of Service Description: USDL and Its Methods*, New York: Springer, pp. 503–519, ISBN 9781461418634, doi:10.1007/978-1-4614-1864-1_20

Mayer, Schroeder et al. (2008) Mayer, Philip, Schroeder, Andreas, and Koch, Nora, 2008, A Model-Driven Approach to Service Orchestration, In: *2008 IEEE International Conference on Services Computing (SCC)*, Piscataway: IEEE, pp. 533–536, ISBN 9780769532837, doi:10.1109/SCC.2008.91

Meier (2011) Meier, Matthias, 2011, *Verfahren zum emulationsgestützten MES-Engineering für die Photovoltaikindustrie*, *IPA-IAO Forschung und Praxis*, vol. 508, Heimsheim: Jost-Jetter, ISBN 9783939890768, Stuttgart, University, Ph.D. thesis, 2011

Meier, Seidelmann et al. (2010) Meier, Matthias, Seidelmann, Joachim, and Mezgár, István, 2010, ManuCloud: The Next-

Generation Manufacturing as a Service Environment, *ERCIM News* **vol. 2010**(83) pp. 33–44

Molcho, Zipori et al. (2008) — Molcho, Gila, Zipori, Y., Schneor, Ronit, Rosen, O., Goldstein, D., and Shpitalni, Moshe, 2008, Computer aided manufacturability analysis: Closing the knowledge gap between the designer and the manufacturer, *CIRP Annals - Manufacturing Technology* **vol. 57**(1) pp. 153–158, doi:10.1016/j.cirp.2008.03.046

Mourtzis and Doukas (2014a) — Mourtzis, Dimitris and Doukas, Michael, 2014a, Design and Planning of Manufacturing Networks for Mass Customisation and Personalisation: Challenges and Outlook, *Procedia CIRP* **vol. 19** pp. 1–13, doi:10.1016/j.procir.2014.05.004

Mourtzis and Doukas (2014b) — Mourtzis, Dimitris and Doukas, Michael, 2014b, The Evolution of Manufacturing Systems: From Craftsmanship to the Era of Customisation, In: Modrák, Vladimír and Semančo, Pavol (eds.), *Handbook of Research on Design and Management of Lean Production Systems*, Hershey: IGI Global, Advances in logistics, operations, and management science (ALOMS) book series, pp. 1–29, ISBN 9781466650398, doi:10.4018/978-1-4666-5039-8.ch001

Muckenhirn (2005) — Muckenhirn, Ralf, 2005, *Konfigurierbares Leitsystem für modulare Montagezellen am Beispiel von Festplatten*, *IPA-IAO Forschung und Praxis*, vol. Nr. 420, Heimsheim: Jost-Jetter, ISBN 3936947635, Stuttgart, University, Ph.D. thesis, 2005

myOpenFactory Software GmbH (2009)
myOpenFactory Software GmbH, 2009, myOpenFactory Standard 4.0, URL `http://myopenfactory.com/DOWNLOADS/myOpenFactory-Standard-4.0.zip` (2013-05-04)

National Research Council (1995)
National Research Council, 1995, *Unit Manufacturing Processes: Issues and Opportunities in Research*, Washington D.C.: National Academies Press, ISBN 0309596440

Negri, Fumagalli et al. (2016) Negri, Elisa, Fumagalli, Luca, Garetti, Marco, and Tanca, Letizia, 2016, Requirements and languages for the semantic representation of manufacturing systems, *Computers in Industry* **vol. 81** pp. 55–66, doi:10.1016/j.compind.2015.10.009

Neo Technology Inc. (2016) Neo Technology Inc., 2016, The Neo4j Manual v2.3.2: Cypher Query Language, URL `http://neo4j.com/docs/stable/cypher-query-lang.html` (2016-03-14)

Neumann (2015) Neumann, Michael, 2015, *Methode für eine situationsbasierte Adaption und Absicherung der Produktionsfähigkeit in der Serienmontage*, *Stuttgarter Beiträge zur Produktionsforschung*, vol. 40, Stuttgart: Fraunhofer Verlag, ISBN 3839608163, Stuttgart, University, Ph.D. thesis, 2015

Nußbaum (2011) Nußbaum, Christopher Lee, 2011, *Modell zur Bewertung des Wirkungsgrades von Produk-*

tkomplexität, *Edition Wissenschaft Apprimus*, vol. 2011, No. 10, Aachen: Apprimus-Verlag, ISBN 3863590236, Aachen, RWTH, Ph.D. thesis, 2011

O'Connor, Knublauch et al. (2005)
O'Connor, Martin, Knublauch, Holger, Tu, Samson, Grosof, Benjamin, Dean, Mike, Grosso, William, and Musen, Mark, 2005, Supporting Rule System Interoperability on the Semantic Web with SWRL, In: Gil, Yolanda, Motta, Enrico, Benjamins, V. Richard, and Musen, Mark A. (eds.), *The Semantic Web – ISWC 2005: Proceedings of the 4th International Semantic Web Conference, Galway, Ireland, November 6–10, 2005*, Berlin: Springer, *Lecture Notes in Computer Science*, vol. 3729, pp. 974–986, ISBN 9783540297543, doi:10.1007/11574620_69

Ost and Mandel (2009)
Ost, Stefanie and Mandel, Jörg, 2009, Kundenauftragsspezifische Produktionsnetzwerke in der Automobilindustrie, *ZWF Zeitschrift für wirtschaftlichen Fabrikbetrieb* **vol. 104**(3) pp. 164–169

Ostgathe (2012)
Ostgathe, Martin, 2012, *System zur produktbasierten Steuerung von Abläufen in der auftragsbezogenen Fertigung und Montage*, *Forschungsberichte IWB*, vol. 265, München: Herbert Utz Verlag, ISBN 9783831642069, Munich, Technical University, Ph.D. thesis, 2012

Ouzounis (2001) Ouzounis, Evangelos, 2001, *An Agent-Based Platform for the Management of Dynamic Virtual Enterprises*, Berlin, Technical University, Ph.D. thesis, doi:10.14279/depositonce-390

Papazoglou and van den Heuvel (2011) Papazoglou, Michael P. and van den Heuvel, Willem-Jan, 2011, Blueprinting the Cloud, *IEEE Internet Computing* **vol. 15**(6) pp. 74–79, doi:10.1109/MIC.2011.147

Patzak and Rattay (2014) Patzak, Gerold and Rattay, Günter, 2014, *Projektmanagement: Leitfaden zum Management von Projekten, Projektportfolios und projektorientierten Unternehmen*, Wien: Linde, 6th ed., ISBN 3714302662

Pfrommer, Stogl et al. (2014) Pfrommer, Julius, Stogl, Denis, Aleksandrov, Kiril, Schubert, Viktor, and Hein, Bjorn, 2014, Modelling and Orchestration of Service-Based Manufacturing Systems via Skills, In: *2014 IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, Piscataway: IEEE, ISBN 9781479948451, doi:10.1109/ETFA.2014.7005285

Piller (1998) Piller, Frank T., 1998, *Kundenindividuelle Massenproduktion: Die Wettbewerbsstrategie der Zukunft*, München: Carl Hanser Verlag, ISBN 9783446193369

Piller (2007) Piller, Frank T., 2007, Observations on the present and future of mass customization, *International Journal of Flexible Manufacturing*

Systems **vol. 19**(4) pp. 630–636, doi:10.1007/s10696-008-9042-z

Pratt, Anderson et al. (2005) Pratt, Michael J., Anderson, Bill D., and Ranger, Tony, 2005, Towards the standardized exchange of parameterized feature-based CAD models, *Computer-Aided Design* **vol. 37**(12) pp. 1251–1265, doi:10.1016/j.cad.2004.12.005

Rahman, Sadik et al. (2008) Rahman, M. Alade, Sadik, Sarmad, Ali, Arshad, Ahmad, H. Farooq, and Suguri, Hiroki, 2008, Agent-based modelling of supply chain management in a Virtual Enterprise, In: *2008 IEEE 2nd International Conference on Digital Ecosystems and Technologies (DEST)*, Piscataway: IEEE, pp. 518–525, ISBN 1424414903, doi:10.1109/DEST.2008.4635215

Ramesh and Devadasan (2007) Ramesh, G. and Devadasan, S. R., 2007, Literature review on the agile manufacturing criteria, *Journal of Manufacturing Technology Management* **vol. 18**(2) pp. 182–201, doi:10.1108/17410380710722890

Rauschecker and Stöhr (2012) Rauschecker, Ursula and Stöhr, Matthias, 2012, Using manufacturing service descriptions for flexible integration of production facilities to manufacturing clouds, In: Katzy, Bernhard (ed.), *2012 18th International ICE Conference on Engineering, Technology and Innovation (ICE)*, Piscataway: IEEE, ISBN 9781467322751, doi:10.1109/ICE.2012.6297693

Rauschecker, Meier et al. (2011) Rauschecker, Ursula, Meier, Matthias, Muckenhirn, Ralf, Yip, Arthur L. K., Jagadeesan, Ananda P., and Corney, Jonathan, 2011, Cloud-Based Manufacturing-as-a-Service Environment for Customized Products, In: Cunningham, Paul and Cunningham, Miriam (eds.), *eChallenges 2011: Conference and exhibition, 26-28 October, Florence, Italy*, Dublin: IIMC, International Information Management Corporation, ISBN 1905824274

Rauschecker, Stöhr et al. (2013) Rauschecker, Ursula, Stöhr, Matthias, and Schel, Daniel, 2013, Requirements and Concept for a Manufacturing Service Management and Execution Platform for Customizable Products, In: *Proceedings of the ASME 8th International Manufacturing Science and Engineering Conference MSEC 2013*, New York: ASME, ISBN 9780791855461, doi:10.1115/MSEC2013-1021

Rauschecker, Stock et al. (2014) Rauschecker, Ursula, Stock, Daniel, Stöhr, Matthias, and Verl, Alexander, 2014, Connecting factories and related IT environments to manufacturing clouds, *International Journal of Manufacturing Research* **vol. 9**(4) pp. 389–407, doi: 10.1504/IJMR.2014.066664

Reichert and Weber (2012) Reichert, Manfred and Weber, Barbara, 2012, *Enabling Flexibility in Process-Aware Information Systems: Challenges, Methods, Technologies*, Berlin: Springer, ISBN 9783642304088

Reichwald and Piller (2009) Reichwald, Ralf and Piller, Frank T., 2009, *Interaktive Wertschöpfung: Open Innovation, Individualisierung und neue Formen der Arbeitsteilung*, Wiesbaden: Gabler Verlag / GWV Fachverlage, 2nd ed., ISBN 9783834909725

Reichwald, Möslein et al. (2000) Reichwald, Ralf, Möslein, Kathrin, Sachenbacher, Hans, and Englberger, Hermann, 2000, *Telekooperation: Verteilte Arbeits- und Organisationsformen*, Berlin: Springer, 2nd ed., ISBN 9783542630125

Romero and Molina (2011) Romero, David and Molina, Arturo, 2011, Collaborative networked organisations and customer communities: value co-creation and co-innovation in the networking era, *Production Planning & Control* **vol. 22**(5-6) pp. 447–472, doi:10.1080/09537287.2010.536619

Royere, Haas et al. (2014) Royere, Bill, Haas, Ted, and Michaleczko, Michael, 2014, Code Set Research Overview and Basics, URL `http://www.freedom-group.org/component/content/article/9-information/4-our-research-on-classifications-code-sets.html` (2014-09-28)

Rudolph and Dietrich (2003) Rudolph, Fritz-Nikolai and Dietrich, Jürgen R., 2003, Praktischer Einsatz von CAD- und EDM/PDM-Systemen, *CAD-CAM REPORT* **vol. 2003**(3–6)

Russell and Norvig (2014) Russell, Stuart and Norvig, Peter, 2014, *Artificial Intelligence: A Modern Approach*, Always learning, Harlow: Pearson, 3rd ed., ISBN 9781292024202

Salvador, Forza et al. (2002) Salvador, Fabrizio, Forza, Cipriano, and Rungtusanatham, Manus, 2002, Modularity, product variety, production volume, and component sourcing: theorizing beyond generic prescriptions, *Journal of Operations Management* **vol. 20**(5) pp. 549–575, doi:10.1016/S0272-6963(02)00027-X

Salvador, Rungtusanatham et al. (2004)
Salvador, Fabrizio, Rungtusanatham, Manus, and Forza, Cipriano, 2004, Supply-chain configurations for mass customization, *Production Planning & Control* **vol. 15**(4) pp. 381–397, doi:10.1080/0953728042000238818

Salvador, de Holan et al. (2009) Salvador, Fabrizio, de Holan, P. Martin, and Piller, Frank T., 2009, Cracking the Code of Mass Customization, *MIT Sloan Management Review* **vol. 50**(3) pp. 70–79

Santana, Aparecida do Nascimento Rebelatto et al. (2014)
Santana, Naja B., Aparecida do Nascimento Rebelatto, Daisy, Périco, Ana E., and Mariano, Enzo B., 2014, Sustainable development in the BRICS countries: an efficiency analysis by data envelopment, *International Journal of Sustainable Development & World Ecology* **vol. 21**(3) pp. 259–272, doi:10.1080/13504509.2014.900831

Schmitz (2013) Schmitz, Barb, 2013, Demands for Increased Product Customization on the Rise, URL `http://creo.ptc.com/2013/03/25/demands-for-increased-product-customization-on-the-rise/` (2015-03-24)

Schönsleben (2011) Schönsleben, Paul, 2011, *Integrales Logistikmanagement: Operations und Supply Chain Management innerhalb des Un-*

ternehmens und unternehmensübergreifend, Berlin: Springer, ISBN 3642203809

Schuh and Meyer (2009) Schuh, Günther and Meyer, Jan C., 2009, Kundenorientierte Gestaltung von Lieferketten: "Supply Chain Segmentation", *wt Werkstattstechnik online* **vol. 99**(4) pp. 244–249

Schuh, Boos et al. (2009) Schuh, Günther, Boos, Wolfgang, and Völker, Magdalena, 2009, Bewertung von Aufwand und Nutzen in Kooperationen: "Net-Check"-Verfahren zum Bewerten der Kooperationsgüte in Produktionsnetzwerken, *wt Werkstattstechnik online* **vol. 99**(4) pp. 216–219

Schulte, Hoenisch et al. (2014) Schulte, Stefan, Hoenisch, Philipp, Hochreiner, Christoph, Dustdar, Schahram, Klusch, Matthias, and Schuller, Dieter, 2014, Towards Process Support for Cloud Manufacturing, In: Reichert, Manfred (ed.), *2014 IEEE 18th International Enterprise Distributed Object Computing Conference (EDOC)*, Piscataway: IEEE, pp. 142–149, ISBN 9781479954704, doi:10.1109/EDOC.2014.28

SCRA (2006) SCRA, South Carolina Research Authority, 2006, STEP Application Handbook: ISO 10303, URL `https://pdesinc.org/downloadable_files/STEPapplicationhandbook63006BF.pdf` (2015-11-26)

SEMI E139-0709 (2009) SEMI, Semiconductor Equipment and Materials International, SEMI E139-0709, 2009, Specification for Recipe and Parameter Management (RaP)

Senn (1992) Senn, James A., 1992, Electronic Data Interchange, *Information Systems Management* **vol. 9**(1) pp. 45–53, doi:10.1080/10580539208906848

Seth, Deshmukh et al. (2006) Seth, Nitin, Deshmukh, S. G., and Vrat, Prem, 2006, A conceptual model for quality of service in the supply chain, *International Journal of Physical Distribution & Logistics Management* **vol. 36**(7) pp. 547–575, doi:10.1108/09600030610684971

Shepherd and Günter (2011) Shepherd, Craig and Günter, Hannes, 2011, Measuring Supply Chain Performance: Current Research and Future Directions, In: Fransoo, Jan C., Waefler, Toni, and Wilson, John R. (eds.), *Behavioral Operations in Planning and Scheduling*, Berlin: Springer, pp. 105–121, ISBN 9783642133817, doi:10.1007/978-3-642-13382-4_6

Shukor and Axinte (2009) Shukor, Syaimak A. and Axinte, Dragos A., 2009, Manufacturability analysis system: issues and future trends, *International Journal of Production Research* **vol. 47**(5) pp. 1369–1390, doi:10.1080/00207540701589398

Sicilia (2006) Sicilia, Miguel-Ángel, 2006, Metadata, semantics, and ontology: Providing meaning to information resources, *International Journal of Metadata, Semantics and Ontologies* **vol. 1**(1) pp. 83–86, doi:10.1504/IJMSO.2006.008773

SiLA (2013) SiLA, Standardisation in Lab Automation, 2013, Device Control and Data Interface

Specification, Rapperswill: SiLA Consortium, URL http://www.sila-standard.org/documents/2014/03/sila-device-control-data-interfaces-specifications.pdf (2016-01-04)

Simão, Stadzisz et al. (2006) Simão, Jean M., Stadzisz, Paulo C., and Morel, Gérard, 2006, Manufacturing execution systems for customized production, *Journal of Materials Processing Technology* **vol. 179**(1-3) pp. 268–275, doi:10.1016/j.jmatprotec.2006.03.064

Simon, Zitzlsberger et al. (2014)
Simon, Dominik, Zitzlsberger, Sabine, Wagner, Julia, Kern, Lisa, Maurer, Christoph, Haller, Dieter, and Reinhart, Gunther, 2014, Forming Plastic Shields on a Reconfigurable Tooling System, In: Zaeh, Michael F. (ed.), *Enabling Manufacturing Competitiveness and Economic Sustainability: Proceedings of the 5th International Conference on Changeable, Agile, Reconfigurable and Virtual Production (CARV 2013), October 6–9, 2013, Munich, Germany*, Cham: Springer, pp. 73–78, ISBN 9783319020532, doi:10.1007/978-3-319-02054-9_13

Slack, Chambers et al. (2010) Slack, Nigel, Chambers, Stuart, and Johnston, Robert, 2010, *Operations Management*, Harlow: Pearson, 6th ed., ISBN 9780273730460

Stadtler (2005) Stadtler, Hartmut, 2005, Production Planning and Scheduling, In: Stadtler, Hartmut and Kilger, Christoph (eds.), *Supply Chain Management and Advanced Planning: Concepts,* *Models, Software and Case Studies*, Berlin: Springer, pp. 197–214, ISBN 9783540220658

Stark (2015) Stark, John, 2015, *Product Lifecycle Management, Volume 1: 21st Century Paradigm for Product Realisation*, Cham: Springer, 3rd ed., ISBN 9783319174402

Steger-Jensen and Svensson (2004) Steger-Jensen, Kenn and Svensson, Carsten, 2004, Issues of mass customisation and supporting IT-solutions, *Computers in Industry* **vol. 54**(1) pp. 83–103, doi:10.1016/j.compind.2003.07.007

Stephens (2001) Stephens, Scott, 2001, Supply Chain Operations Reference Model Version 5.0: A New Tool to Improve Supply Chain Efficiency and Achieve Best Practice, *Information Systems Frontiers* **vol. 3**(4) pp. 471–476, doi:10.1023/A:1012881006783

Stoye, Vornholt et al. (2011) Stoye, Michael, Vornholt, Stephan, and Geist, Ingolf, 2011, Management of Flexible Data Exchange Processes in Virtual Product Development, In: Köppen, Veit and Saake, Gunter (eds.), *IWDE 2011: Proceedings of the 2nd International Workshop on Digital Engineering*, pp. 67–74

Stuckenschmidt (2009) Stuckenschmidt, Heiner, 2009, *Ontologien: Konzepte, Technologien und Anwendungen*, Informatik im Fokus, Berlin: Springer, ISBN 9783540793304

Syu, Ma et al. (2012) Syu, Yang, Ma, Shang-Pin, Kuo, Jong-Yih, and FanJiang, Yong-Yi, 2012, A Survey on Automated Service Composition Methods and Related Techniques, In: Moser, Louise (ed.), *2012 IEEE 9th International Conference on Services Computing (SCC)*, Piscataway: IEEE, pp. 290–297, ISBN 9780769547534, doi:10.1109/SCC.2012.91

Tao, Zhang et al. (2011) Tao, Fei, Zhang, Lin, Venkatesh, V. C., Luo, Y., and Cheng, Ying, 2011, Cloud manufacturing: a computing and service-oriented manufacturing model, *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* **vol. 225**(10) pp. 1969–1976, doi:10.1177/0954405411405575

Tao, Zhang et al. (2012) Tao, Fei, Zhang, Lin, and Hu, Yefa, 2012, *Resource Service Management in Manufacturing Grid System*, Hoboken and Salem: John Wiley & Sons and Scrivener Publishing, ISBN 9781118288764

Tiihonen, Felfernig et al. (2014) Tiihonen, Juha, Felfernig, Alexander, and Mandl, Monika, 2014, Personalized Configuration, In: Felfernig, Alexander, Hotz, Lothar, Bagley, Claire, and Tiihonen, Juha (eds.), *Knowledge-Based Configuration: From Research to Business Cases*, Waltham: Morgan Kaufmann, pp. 167–180, ISBN 9780124158177

Tseng, Chang et al. (2005) Tseng, Hwai-En, Chang, Chien-Chen, and Chang, Shu-Hsuan, 2005, Applying case-based reasoning for product configuration in mass customization environments, *Expert Systems with*

Applications **vol. 29**(4) pp. 913–925, doi:10.1016/j.eswa.2005.06.026

Tuma (1998) Tuma, A., 1998, Configuration and coordination of virtual production networks, *International Journal of Production Economics* **vol. 56–57** pp. 641–648, doi:10.1016/S0925-5273(97)00146-1

Ullrich, Vladova et al. (2015) Ullrich, André, Vladova, Gergana, Thim, Christof, and Gronau, Norbert, 2015, Akzeptanz und Wandlungsfähigkeit im Zeichen der Industrie 4.0, *HMD – Praxis der Wirtschaftsinformatik* **vol. 52**(5) pp. 769–789, doi:10.1365/s40702-015-0167-8

VDI (2015) VDI, Gesellschaft Produktion und Logistik, 2015, *VDI-Handbuch Produktionstechnik und Fertigungsverfahren - Band 2: Fertigungsverfahren*, vol. 2, Düsseldorf: Beuth

VDI/VDE 2653 Part 1 (2010) VDI/VDE, Verein Deutscher Ingenieure / Verband der Elektrotechnik, Elektronik und Informationstechnik, VDI/VDE 2653 Part 1, 2010, Multi-agent systems in industrial automation: Fundamentals., Berlin: Beuth

Vernadat (2009) Vernadat, François B., 2009, Enterprise Integration and Interoperability, In: Nof, Shimon Y. (ed.), *Springer Handbook of Automation*, Berlin: Springer, pp. 1529–1538, ISBN 9783540788300, doi:10.1007/978-3-540-78831-7_86

Vokurka and O'Leary-Kelly (2000)

Vokurka, Robert J. and O'Leary-Kelly, Scott W., 2000, A review of empirical research on manufacturing flexibility, *Journal of Operations Management* **vol. 18**(4) pp. 485–501, doi:10.1016/S0272-6963(00)00031-0

Volberda, Morgan et al. (2011) Volberda, Henk W., Morgan, Robert E., Reinmoeller, Patrick, Hitt, Michael A., Ireland, R. Duane, and Hoskisson, Robert E., 2011, *Strategic Management: Competitiveness and Globalization, Concepts and Cases*, Andover: Cengage Learning, ISBN 9781408019184

Walter (2008) Walter, Elizabeth (ed.), 2008, *Cambridge advanced learner's dictionary*, Cambridge University Press, Stuttgart: Klett Sprachen, 3rd ed., ISBN 9780521674683

Wang and Xu (2013) Wang, Xi Vincent and Xu, Xun W., 2013, An interoperable solution for Cloud manufacturing, *Robotics and Computer-Integrated Manufacturing* **vol. 29**(4) pp. 232–247, doi:10.1016/j.rcim.2013.01.005

Wazlawick (2014) Wazlawick, Raul Sidnei, 2014, *Object-Oriented Analysis and Design for Information Systems: Modeling with UML, OCL, and IFML*, Waltham: Morgan Kaufmann, ISBN 9780124186736

Weiss and Schweiggert (2013) Weiss, Michaela and Schweiggert, Franz, 2013, Opportunities and Challenges of the Customization Megatrend: A Mangement Tool to Evaluate Customization Potential, In: *Proceedings of the International Conference on Advanced Research in Business, June 3–5, 2013, London,* *UK*, pp. 39–44, URL http://www.intlafr.com/Londonproceedings.pdf (2015-04-26)

Weller (2010) Weller, Jens, 2010, *Modellgestützte Prozessverbesserung: Entwicklung einer wiederverwendungsorientierten Methode zur durchgängigen Unterstützung der Modellerstellung, -transformation und -nutzung im Rahmen der Prozessverbesserung*, Dresden, Technical University, Ph.D. thesis, URL http://nbn-resolving.de/urn:nbn:de:bsz:14-qucosa-38443 (2015-05-29)

Westkämper (2014) Westkämper, Engelbert, 2014, *Towards the Re-Industrialization of Europe: A Concept for Manufacturing for 2030*, Heidelberg: Springer, ISBN 9783642385018

Wienholdt, Schmidt et al. (2007) Wienholdt, Henrik, Schmidt, Carsten, Schweicher, Benedikt, and Walber, Benjamin, 2007, Grundlagen der überbetrieblichen Auftragsabwicklung, In: Schuh, Günther (ed.), *Effiziente Auftragsabwicklung mit myOpenFactory*, München: Carl Hanser Verlag, pp. 6–30, ISBN 9783446412781

Wilde and Hess (2007) Wilde, Thomas and Hess, Thomas, 2007, Forschungsmethoden der Wirtschaftsinformatik, *Wirtschaftsinformatik* **vol. 49**(4) pp. 280–287, doi:10.1007/s11576-007-0064-z

Witczyński and Pawlak (2005) Witczyński, Maciej and Pawlak, Adam, 2005, Virtual Organizations in the Electronics Sector, In: Camarinha-Matos, Luis M., Afsarmanesh, Hamideh, and Ollus, Martin (eds.), *Virtual Organizations: Systems and Practices*, Boston: Springer, pp. 221–232, ISBN 9780387237572, doi:10.1007/0-387-23757-7_15

Wong and Lesmono (2011) — Wong, Hartanto W. and Lesmono, Dharma, 2011, The value of enhanced customisation in the existence of consumer preferences heterogeneity, In: Spath, Dieter, Ilg, Rolf, and Krause, Tobias (eds.), *Innovation in product and production: Proceedings of the 21th International Conference on Production Research (ICPR), July 31 – August 4, 2011, Stuttgart, Germany*, Stuttgart: Fraunhofer Verlag, ISBN 9783839602935

Wortmann (1991) — Wortmann, John C., 1991, Towards one-of-a-kind Production: The Future of European Industry, In: Eloranta, Eero (ed.), *Advances in Production Management Systems: Proceedings of the 4th IFIP TC5/WG5.7 International Conference on Advances in Production Management Systems (APMS '90), 20–22 August 20–22, 1990, Espoo, Finland*, Burlington: Elsevier, pp. 41–49, ISBN 9780444889195, doi: 10.1016/B978-0-444-88919-5.50010-X

Xu (2012) — Xu, Xun, 2012, From cloud computing to cloud manufacturing, *Robotics and Computer-Integrated Manufacturing* **vol. 28**(1) pp. 75–86, doi:10.1016/j.rcim.2011.07.002

Yan, Ye et al. (2010) — Yan, Jiaqi, Ye, Kang, Wang, Huaiqing, and Hua, Zhongsheng, 2010, Ontology of collaborative manufacturing: Alignment of service-oriented framework with service-dominant logic, *Expert Systems with Applications* **vol. 37**(3) pp. 2222–2231, doi:10.1016/j.eswa.2009.07.051

Yip, Jagadeesan et al. (2011) — Yip, Arthur L. K., Jagadeesan, Ananda P., Corney, Jonathan R., Qin, Yi, and Rauschecker, Ursula, 2011, A front-end system to support cloud-based manufacturing of customised products, In: Harrison, David K., Wood, Bruce M., and Evans, Dorothy (eds.), *Advances in Manufacturing Technology XXV: Proceedings of the 9th International Conference on Manufacturing Research (ICMR2011)*, Glasgow Caledonian University, pp. 193–199, ISBN 9781905866564

Yip, Corney et al. (2013) — Yip, Arthur L. K., Corney, Jonathan R., Jagadeesan, Ananda P., and Qin, Yi, 2013, A Product Configurator for Cloud Manufacturing, In: *Proceedings of the ASME 8th International Manufacturing Science and Engineering Conference MSEC 2013*, New York: ASME, ISBN 9780791855461, doi:10.1115/MSEC2013-1250

Zimmermann (2007) — Zimmermann, Hans-Dieter, 2007, Elektronischer Dokumentenaustausch zwischen Unternehmen, In: Wölfle, Ralf and Schubert, Petra (eds.), *Business Collaboration: Standortübergreifende Prozesse mit Business Software: Praxislösungen im Detail: Fallstudien, Konzepte, Modellierung*, München: Carl Hanser Verlag, pp. 127–134, ISBN 9783446412224

The increasing demand for individualised products, as well as rising product complexity, are challenging while managing production networks. To counter this, it is necessary to efficiently configure agile production networks while reducing the necessary know-how at the same time. This thesis proposes an IT-based method for connecting customisable manufacturing services to do so.

First, this includes the provision of manufacturing services by manufacturers publishing service descriptions on a common platform. These services can then be selected, configured, and connected to establish agile production networks. While configuring the networks, potential dependencies between the combined manufacturing services and their properties must be considered. To support this, the developed system provides recommendations derived from previously-defined connections between manufacturing services.

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