Digital Transformation in the Manufacturing Industry: Technologies and Architectures

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Ein großer Dank gilt meiner Familie
und meinen Freunden, deren Unterstützung
ich zu jeder Zeit hatte.

Abstract

This cumulative dissertation aims to contribute to the field of digital transformation in the manufacturing industry and is based on several scientific publications. Special focus is given to technologies and architectures and, in particular, to three main research topics that will contribute to this area. The first research topic addresses the maintenance of industrial machines. By enhancing static maintenance intervals and shifting to condition-based maintenance or, further, to predictive maintenance, cost and time can be saved, and the likelihood of breakdown can be reduced. Different models help to calculated the optimal number of spare parts or optimize maintenance planning. To predict machine breakdowns, not only statistical methods but also advanced data analytic techniques are necessary. The field of industrial machines is very broad, and even a single company faces the issue of having its components or machines used in several different applications. The development of analysis models is therefore challenging. Concepts for enhancing data analytic techniques through combinations of domain knowledge experience are presented in this dissertation. The growing interest in predictive maintenance has led to various business models in the manufacturing industry. A taxonomy to classify these predictive maintenance business models is presented within this dissertation. Second, a detailed image of a machine or plant can provide valuable information to operators and managers. Therefore, this dissertation addresses the topic of installed base management and digital twins. Insights into the health status of individual components or plants are necessary for timely reactions to events and to support decision making. With the help of a digital representation of a component, machine or plant, new services can also be enabled. The third research topic addresses the increasing importance being place by industry on new services for manufacturing. Products are no longer sold independently but are offered along with services as product-service systems. Furthermore, so-called smart services offer the potential for digital transformations in the manufacturing industry. These services are customer-centric and are based on the usage of various data. In addition knowledge management for smart services is considered. By combining the features described in these topics, digital transformation in the manufacturing industry is driven and enabled. This digital transformation means changes for companies in terms of the technologies and IT architectures used as well as disruptive changes to current business models. However, with the help of digital transformation, customer demand can be satisfied, processes improved or accelerated and new value networks established.

Keywords: Digital Transformation, Manufacturing Industry, Architectures, Predictive Maintenance, Digital Twin, Product-Service-Systems

Zusammenfassung

Diese kummulative Dissertation baut auf mehreren Veröffentlichungen im Rahmen der digitalen Transofrmation in der produzierenden Industrie auf. Hierbei liegt der Fokus auf Architekturen und Modelle in dem Bereich. Drei Hauptthemen werden innerhalb dieser Dissertation behandelt, die alle im Bereich der digitalen Insutrie für produzierende Indsutrie anzusiedeln sind. Als erstes wird die Wartung von Maschinen beleuchtet. Dabei wird häufig nicht mehr mit starren Wartungsintervallen gearbeitet, sondern zustandsbasiert gewartet. Darauf aufsesetzend kann durch Modelle oder künstliche Intelligenz auch eine Vorhersage des optimalen Wartungszeitpunktes getroffen werden. Dadurch können Kosten und Stillstände sowie Stillstandszeiten reduziert werden. Es ist hervorzuheben, dass industrielle Maschinen, die hierbei eingesetzt werden, sehr unterschiedlich sind. Die Entwicklung von Analysemodellen wird dadurch umso komplizierter. In dieser Dissertation werden daher neben Optimierungsmodelle auch Konzepte aufgezeigt, um diese Modelle mit Expertenwissen zu kombinieren und somit einen Mehrwert zu generieren. Im Rahmen einer Taxonomie werden verscheidene Geschäftsmodelle für die vorausschauende Wartung klassifiziert. Im zweiten Hauptteil dieser Dissertation wird der digitale Zwilling und das Management von Fabriken sowie den enthaltenen Maschinen und Komponenten betrachtet. Ein detailiertes Wissen über den aktuellen Zustand von Anlagen und deren Komponenten, erlaubt es Entscheidern schnell Entscheidungen zu treffen und Stillstandszeiten sowie Schäden zu reduzieren und den Output zu maximieren. Durch den digitalen Zwilling werden auch neue Services ermöglicht. Daher beschäfts sich der dritte Hauptteil dieser Disseration mit Produkt-Service-Systemen und neuen Geschäftsmodellen für den Industriegüterbereich und das produzeirende Gewerbe. Produkte werden nicht mehr rein physisch verkauft, sondern mit Services kombiniert um Mehrwerte für Kunden zu schaffen. Smart Services erlauben es die digitale Transformation weiter voranzutreiben. Diese Smart Services sind dabei im großen Stile kundenorientiert und basieren auf der Nutzung und Verarbeitung von Daten. Weiterhin wird Wissensmanagement im Zusammenhang mit Smart Services betrachtet. Durch die Kombination der beschrieben drei Hauptfelder wird die digitale Transformationen ermöglich und kontinuierlich voran getrieben. Die digitale Transformation bedeutet Änderungen der eingesetzten Technologien und IT-Architekturen, aber auch Änderungen in den Geschäftsmodellen oder neue Geschäftsmodelle. Die digitale Transformation bietet jedoch für Unternehmen die Möglichkeit Kundenbedürfnisse besser zu verstehen und zu erfüllen sowie interne Prozesse als auch Prozesse zum Kunden zu verbessern oder zu beschleunigen. Letztendlich können auch neue Wertschöpfungsnetzerke hierdurch entstehen.

Schlagworte: Digitale Transformation, Industrie, Architekturen, Vorausschauende Wartung, Digitaler Zwilling, Produkt-Service-Systeme

Management Summary

The digital transformation of the manufacturing industry is inescapable. Increasingly, companies are seeing digital transformation as a way to enable new business models, increase revenue opportunities, and achieve greater competitiveness. To address digital transformation in research and practice, architectures and models can help to structure the relevant topics and show their potential. They can thus also help practitioners to structure the topic and implement technologies in companies. The present dissertation, "Digital Transformation in the Manufacturing Industry: Technologies and Architectures", aims to contribute to this challenge. The dissertation is divided into three main parts.

The first part of the dissertation is called Predictive maintenance for industrial machines (Chapter 3). The maintenance of industrial machines is essential to keep their availability high and avoid production loss or breakdown. For machine maintenance, it is important to have spare parts in stock or available at short notice. First, an optimization model is developed to calculate the optimal number of spare parts to keep in stock. Several influence factors determine the number of spare parts in stock for a specific company, for example, the cost of the spare parts, the probability of default for the specific machine and the cost of a breakdown if spare parts are not available and the machine is idle. The developed optimization model considers the tradeoff between breakdown costs and spare part provisioning costs using the condition monitoring data for machines to obtain an actual view of the breakdown probability. With the help of condition monitoring data, the probability of default for each component can be calculated or retrieved. To determine the optimum number of spare parts to keep in stock, an algorithm is developed based on the optimization model that is shown in Figure 1. In addition to the model,

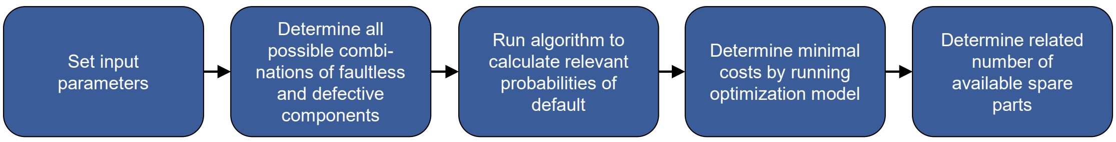

Figure 1: General procedure to determine the optimal number of available spare parts

a new service concept is proposed in which the number of spare parts held in stock can be adjusted by the customer in each period. This means that spare parts do not have to be bought, which is an advantage, but a lump-sum fee for the provision is charged. A new business model could be proposed for this structure because the service provider is responsible for the availability of machines. Therefore, he or she is also responsible for maintaining the machines and components to ensure the agreed-upon availability level. The experimental results show that by using the model, the optimum number of spare parts based on the lowest costs can be determined. By combining the optimization model with the new service concept, new business models can be supported and customer-centric services offered. For industrial machines, the point in time at which they are maintained is essential. A well-suited maintenance policy is needed to ensure that machine downtime is reduced as much as possible. Infrequent maintenance activities increase the risk of potential machine breakdowns, which often result in long repair times and high financial losses. Overly frequent maintenance leads to machine downtime for unnecessary maintenance and unnecessary maintenance costs. To help practitioners determine the optimal maintenance policy for machines, a decision support system, including an optimization model, is developed. Figure 2 shows the steps to determine the optimal maintenance policy.

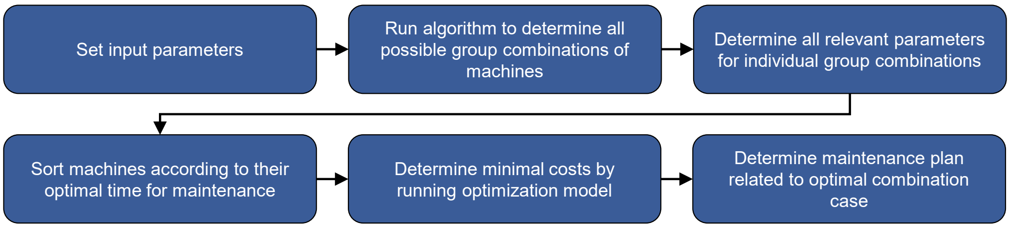

Figure 2: General procedure to determine the optimal maintenance activities

The goal is to group the timing of machine maintenance to save maintenance costs and minimize total costs. Therefore, it must also be considered that each machine will not be maintained at its optimal point in time when it is grouped together with others. This can result, for example, in maintenance activities being performed too early or too late, with the latter having a higher breakdown risk. Therefore, the best overall combination needs to be found. As stated above, it is important to know the actual condition of a machine or component as retrieved via sensor data. It is important not only to have a probability of default but also to recognize anomalies, and it can be quite challenging to identify the root cause of anomalies in the operations of industrial machines. A hybrid-learning machine monitoring approach is developed to address this challenge. The approach is presented in Figure 3 and consists of three modules. In the first module, anomalies for components of industrial machines or for the machines itself are detected. This anomaly detection is based on operational data, which can be very frequent, and detection can be performed using either statistical approaches or artificial intelligence. The approach aims to be generally applicable to different use cases, but an exemplary use case for conveyor belts with the application of long short-term memory (LSTM) is presented for the anomaly detection module. The classifier module (second module) obtains the relevant data passed on from the anomaly detection module. For each possible root cause, a probability is calculated, and these are both given to the monitor module (third module).

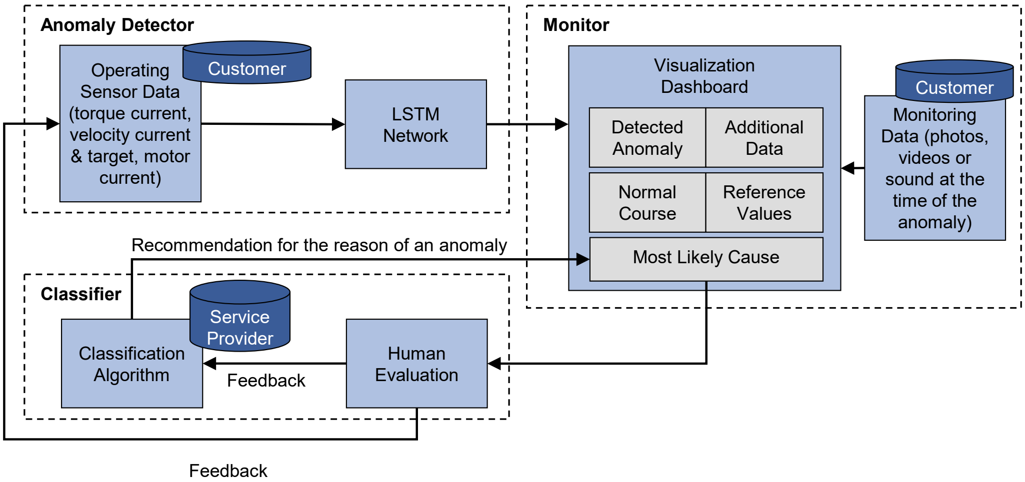

Figure 3: The developed machine monitoring approach

The monitor module serves as the central user interface for the domain experts, allowing them to view all necessary data. Feedback loops are important to ensure validation and improvement of the previously described modules. This is also relevant for anomalies that are new or root causes that cannot yet be identified. Predictive maintenance is a promising approach in the manufacturing industry, based on which new business models are emerging and current business models are being adjusted. Herein, a taxonomy for classifying predictive maintenance business models is developed, and with the help of this taxonomy, business models of 113 real-world companies are analyzed. A cluster analysis is performed, and the clusters are analyzed using a new visualization technique based on an autoencoder application. The result is six archetypes: hardware development, platform provider, all-in-one, information manager, consulting and analytics provider. An overview of the archetypes and their characteristics can be found in Table 1. These archetypes can help companies review their existing business models and compare themselves to others. A strategic orientation can be determined on that basis.

The second main part of this dissertation is titled Digital twins and installed base management in the industrial context (Chapter 4). High availability is required of industrial machines, and this is achieved, among other approaches, by predictive maintenance. Machines and components are involved in different industrial applications, and establishing reliable models and architectures is challenging. It is even more important to obtain a digital representation of a machine, a so-called digital twin. Digital twins are virtual representations of a component, machine or plant and can be created for different purposes. A promising way to enable digital twins in the manufacturing industry is through installed base management. Installed base management goes beyond asset management by providing insights into the physical assets of a plant as well as the interplay of components.

Table 1: Predictive maintenance business model archetypes

	Archetype 1	**Archetype 2**	**Archetype 3**	**Archetype 4**	**Archetype 5**	**Archetype 6**
Label	Hardware development	Platform provider	All-in-one	Information manager	Consulting	Analytics provider
Key activities	Hardware development	Provision of an application platform	Universal offer	Edge computer development	Consulting	Software development
Value promise	Condition monitoring	Forecasting	All-in-one solution	Condition monitoring	Condition monitoring	Forecasting
Payment model	One-time sales	Hybrid	Hybrid	Hybrid	Project	Time basis
Deployment channel	Physically	Physically + www (cloud)	Physically + www (cloud)	Physically + www (cloud)	Physically	www (cloud)
Customer segment	No industry focus	Manufacturing industry	No industry focus	Manufacturing Industry	No industry focus	No industry focus
Clients	B2B	B2B	B2B	B2B + B2B2B	B2B	B2B
Information layer	Object sensing and information gathering	Application and services	Multiple	Multiple & information delivering	Application and services	Application and services & information handling
Share in sample (113)*	21%	12%	27%	5%	13%	20%
Example company	Rockwell Automation	Test Motors	National Instruments	IXON	Hitachi Consulting	Senseye

*Due to rounding inaccuracy the sum is not exactly 100%

The usage of data such as condition monitoring data, for example, is an important aspect of digital twins. To set the basis for a digital twin, an integrated installed base management system is developed within an action design research (ADR) approach. The applied research approach can be found in Figure 4. ADR combines action research and design research in an integrated approach to ensure practical relevance as well as IS methodological competences. Within the comprehensive ADR approach presented, researchers from a German university, employees at an engineering and automation company and end users work closely together. In the first step, the problem was formulated by the ADR team. A literature review in the field of installed base management and installed base management architectures helped to set the stage and to obtain an overview of the state of the research. Through iterative cycles and with the help of a focus group discussion, the final integrated installed base management system was developed, including an extensive applicability check that was performed with the help of a real-world demonstration machine. The final installed base management system is shown in Figure 5. In manufacturing companies, different data sources are used, for example enterprise resource planning (ERP) systems, manufacturing execution systems (MES), customer relationship management (CRM) systems and many others.

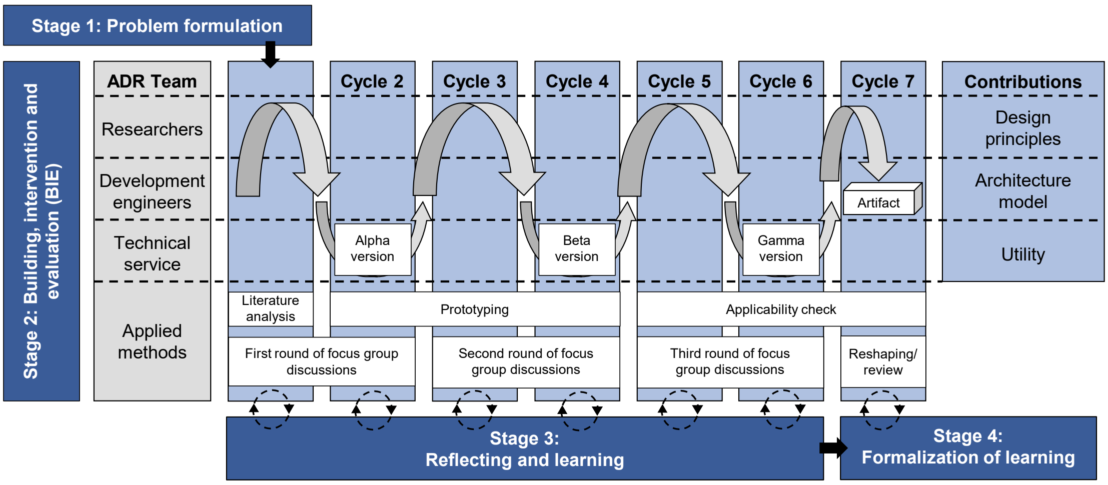

Figure 4: Research design based on the ADR approach from (Sein et al., 2011)

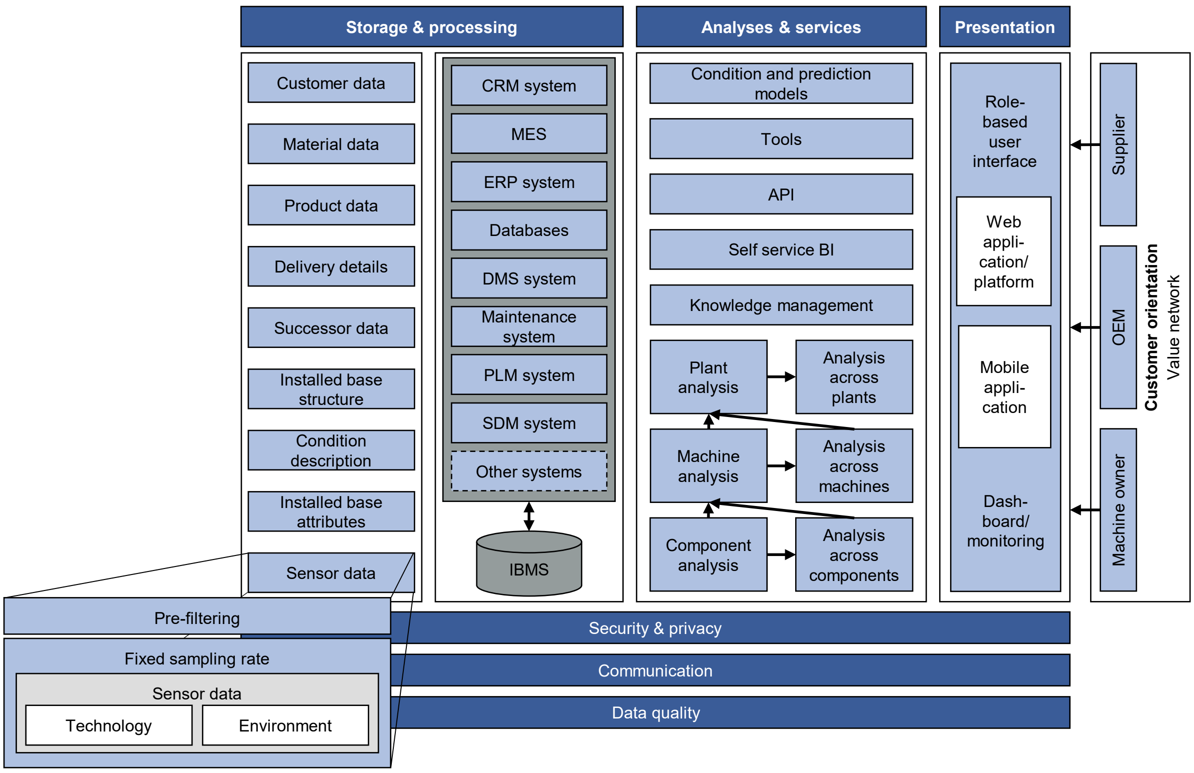

Figure 5: Integrated installed base management system

Data collected during the life cycle of the machine need to be combined with actual data from operations to obtain a comprehensive view of an individual asset. This can be performed not only for a single component or machine but also for a whole plant and through different value networks.

The third and last section, called Product service systems and business models in the industrial context (Chapter 5), describes new ways of combining physical products and services. Product-service systems (PSS) and smart services enable new business models and new revenue challenges. Additionally, customers often need a guarantee that their machine will be available. To help researchers and practitioners develop PSS, a modeling framework for PSS design is proposed (see Figure 6). This framework utilizes the systems modeling language (SysML). To show the applicability of the framework in practice, a use case with a German automation company is established and the model applied.

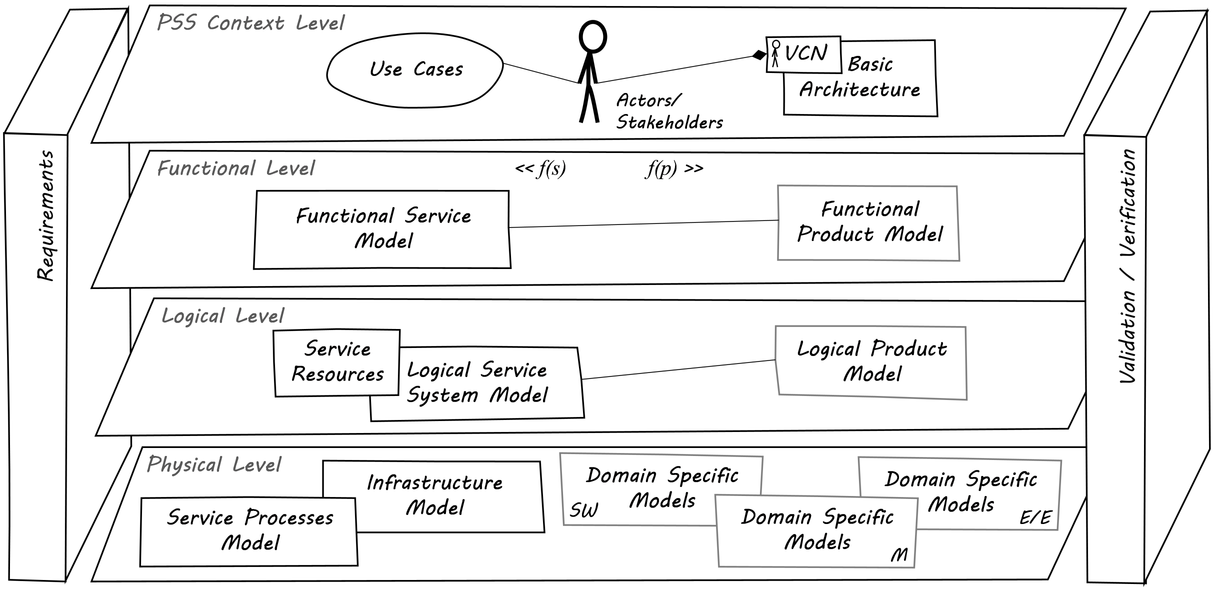

Figure 6: General structure of the integrated PSS modeling framework

In recent years, the term “smart services” has gained increasing popularity. Smart services address individual customer needs and are enabled by information and communications technology. Cocreating value between customers and smart services providers is a key aspect of smart services. To structure the topic and identify a promising research gap, a structured literature review according to Webster and Watson is performed. In total, 109 relevant papers are analyzed in detail. First, a definition for smart services is developed, and then the papers are clustered into 13 topics based on the smart service life cycle. These topics are discussed in detail to show the actual state of research in each of the 13 topics. The results are visualized in the form of a heat map. This heat map show cold and hot areas based on how much research is already conducted in each field. Finally, suggestions for further research are provided.

Following this extensive smart services literature review, knowledge management was identified as a promising approach to be used in combination with smart services. Smart services are individual services that aim to adapt to new customer needs and requirements in a short time. Often, various types of data are used to offer such smart services, and knowledge is needed. The literature shows that much research is currently being conducted in the field of combining smart services with knowledge management. To address this challenge, requirements for knowledge management are developed from the literature for different types of smart services. A reference model is further developed to show diverse designs for a knowledge management system for smart services (KMSSS) (see Figure 7). Predictive maintenance is used as an example smart service to check the applicability of the KMSSS. A value network between component suppliers, machine builders and machine operators are considered, based up which recommendations for the KMSSS design are presented and discussed. When using new technologies and architectures, new business

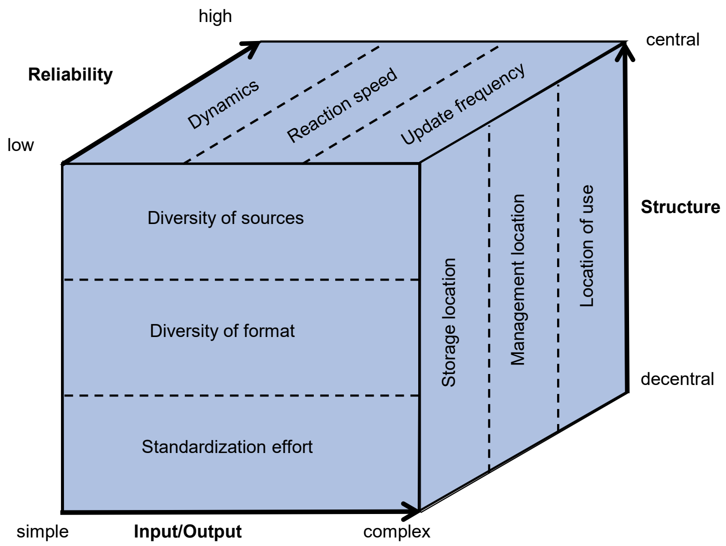

Figure 7: Knowledge management system for smart services reference model

models also emerge. By knowing more about industrial machines, smart services such as predictive maintenance can be offered. As previously described, machines are now offered along with services as PSS. Industrial machines are often very expensive and have a long operating life. Therefore, industry requirements have expanded to asking vendors or service providers to ensure a certain level availability or output from a machine. The guaranteed availability of systems or products has been seen in IT sectors for many years. An existing concept in the development of availability-oriented business models is validated here based on an industrial use case. With the help of this use case, the availability-oriented business model is instantiated. The uses case focus on predictive maintenance in the industrial sector. To instantiate the concept through a use case, first, personas are identified and described in detail. A customer journey helps to concretize the use case and identify the scenarios and value networks to be realized. A real-world demonstration machine is build and used for evaluation purposes. The value network map created within this research can be found in Figure 8. For industrial machines a value network of component suppliers, machine builders and machine operators often exists. The question who of the partners act as a service provider arise based on the individual value network. The results show the applicability of the model and provide suggestions for further research.

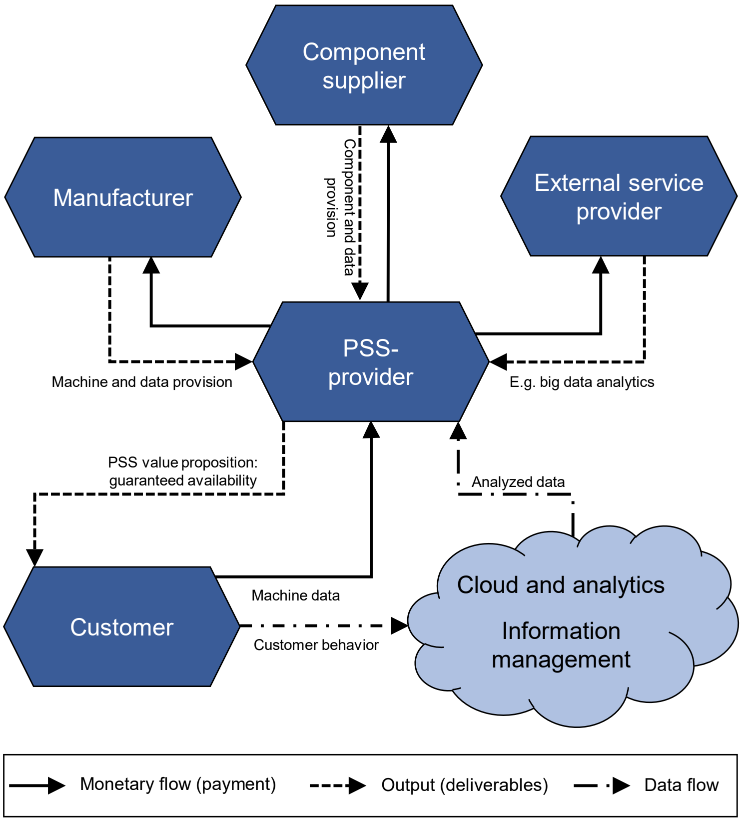

Figure 8: Value network map

Contents

List of Figures

List of Tables

List of Abbreviations

ADR

Action Design Research

API

Application Programming Interface

B2B

Business-to-Business

B2B2B

Business-to-Busines-to-Business

BI

Business Intelligence

BIE

Building, Intervention and Evaluation

BISE

Business & Information Systems Engineering

BITKOM

Bundesverband Informationswirtschaft, Telekommunikation und neue Medien e.V.

CAD

Computer-Aided Design

CBA

Certigied-Based Authentication

CIRP

College International pour la Recherche en Productique

CPS

Cyber-Physical System

CRM

Customer Relationship Management

CSS3

Cascading Style Sheets

DMS

Document Management System

DSS

Decision Support System

E/E

Electrics/Electronics

EM

Electronic Markets

ERP

Enterprise Resource Planning

GOR

German Operations Research Society

HIL

Hardware-in-the-Loop

HTML

Hypertext Markup Language

IBMS

Installed Base Management System

ICT

Information and Communications Technology

IESS

International Conference on Exploring Service Science

IIOT

Industrial Internet of Things

IoT

Internet of Things

IPSS

Industrial Product-Service Systems

ISEB

Information Systems and e-Business Management

ISO

International Organization for Standardization

ISR

Information Systems Research

ITIL

Information Technology Infrastructure Libary

IWI

Institut für Wirtschaftsinformatik, Leibniz Universität Hannover

KMSSS

Knowledge Management System for Smart Services

KPI

Key Performance Indicator

KSCM

Kaiserslautern System Concretization Model

LNBIP

Lecture Notes in Business Information Processing

LSTM

Long Short-Term Memory

M2M

Machine-to-Machine

MBSE

Model-Based Systems Engineering

MES

Manufacturing Execution System

MQTT

Message Queuing Telemetry Transport

NoSQL

Not only SQL

OEE

Overall Equipment Effectiveness

OEM

Original Equipment Manufacturer

OPC

Open Platform Communications

OPC UA

OPC Unified Architecture

OR

Operations Research

PDM

Product Data Management

PLC

Programmable Logic Controller

PLM

Product Lifecycle Management

PSS

Product Service Systems

RAMI 4.0

Reference Architecture Model for Industrie 4.0

RFID

Radio-Frequency Identification

RQ

Research Question

SDM

Sensor-Data-Management

SMACIT

Social, Mobile, Analytics, Cloud and, Internet of Things

SQL

Structured Query Language

SysML

Systems Modeling Language

TSISQ

Tool for Semantic Indexing and Similarity Queries

TSN

Time-Sensitive Networking

UML

Unified Modeling Language

VCN

Value-Creation Network

VDMA

Verband Deutscher Maschinen- und Anlagenbau

VNA

Value Network Analysis

VPN

Virtual Private Network

WWW

World Wide Web

ZVEI

Zentralverband Elektrotechnik- und Elektronikindustrie

0 Overview of publications and task allocation

The following section provides an overview of the papers relevant to this dissertation (see Table 2). Eight peer reviewed papers published in different journals and conference proceedings in the years 2017, 2018 and 2019 are included in this dissertation. Two papers are submitted to journals at the moment and are under review. The outlets of the publications and submitted papers are Operations Research Proceedings 2016 and 2017, Wirtschaftsinformatik Proceedings 2017, Lecture Notes in Business Information Processing (LNBIP), Information Systems and e-Business Management (ISEB), Electronic Markets (EM), Business & Information Systems Engineering (BISE) and Procedia CIRP. Further, three nonpeer-reviewed publications in the IWI Discussions Paper Series are included. Each of these papers was written by a different group of coauthors, for a total of 14 involved coauthors. In alphabetical order, these coauthors, in addition to the author of this dissertation, are: Hristo Apostolov, Jan C. Aurich, Alexander Axjonow, Michael H. Breitner, Sonja Dreyer, Martin Eigner, Dennis Eilers, Matthias Fischer, Lukas Grützner, Christoph F. Herder, Leonie Jürgens, Patrick Kölsch, Benedikt Lebek, Jens Passlick and Ines Stoll. All papers contribute to the field of digital transformation in the manufacturing industry.

The manufacturing industry is characterized by the use of industrial machines. The uptime of these machines is essential and downtime comes with high costs; however, with the help of condition monitoring and appropriate maintenance strategies, downtimes can be reduced. The paper “Optimizing Machine Spare Parts Inventory Using Condition Monitoring Data” (Dreyer et al., 2018) was presented at the Annual International Conference of the German Operations Research Society (GOR) in 2016 in Hamburg, Germany, and it develops an optimization model to determine the optimal number of spare parts. This optimization models aims to achieve a balance between the provision costs of spare parts and possible breakdown costs. The model also considers the actual condition of machines in the case of condition monitoring. In this work, I was primarily involved in the development of the mathematical model and the conceptual development of the algorithm. In addition to the optimal number of spare parts in stock, an optimized maintenance plan is required. Given insights into the machines through condition monitoring, grouping machines together and providing maintenance to them at the same time can save costs. The paper “Maintenance Planning Using Condition Monitoring Data” (Olivotti, Passlick, Dreyer, et al., 2018) provides an optimization model that can determine the optimal point in time for providing maintenance to several industrial machines. The condition of each individual machine is used to group them, and then the tradeoff is evaluated between providing maintenance to machines at a nonoptimal point by grouping them and the general maintenance costs. Grouping helps to avoid downtimes and save costs. I presented this paper at the Annual International Conference of the GOR in 2017 in Berlin, Germany. I was responsible for the literature search and analysis as well as for the writing of the paper. I developed the mathematical model together with my coauthors, and we also together developed the algorithm conceptually, while I worked it out more in detail. Another promising approach is to use machine learning techniques to gain valuable in- sights from the sensor data of industrial machines. The concept of combining machine learning approaches and domain experience is presented in the paper "Combining Machine Learning and Domain Experience: A Hybrid-Learning Monitor Approach for Industrial Machines" (Olivotti, Passlick, Axjonow, et al., 2018). I presented this paper at the 9th International Conference on Exploring Service Science in in 2018 in Karlsruhe, Germany, where the paper was nominated for one of three best paper awards at the conference. I was responsible for the writing of the paper and particularly for the discussion and industrial application as well as the Product-Service-Systems (PSS) context. Further I developed the machine monitoring approach together with my coauthors and participated in the data analysis. Predictive maintenance has broad applications and characteristics. A taxonomy of predictive maintenance business models helps companies to position themselves and evaluate their existing business models. Such a taxonomy is developed in the paper "Predictive Maintenance as an Internet of Things enabled Business Model: Toward a Taxonomy" (Passlick et al., 2019). The paper is currently submitted to a journal and under review. I participated in the development of the taxonomy together with my coauthors. Further, we together developed the presented archetypes and clusters. Predictive maintenance hast strong influence on the quality management of industrial companies. The German paper "Einflüsse der Digitalisierung auf das Qualitätsmanagement und die Notwendigkeit einer integrierten Betrachtungsweise anhand eines Referenzmodells" (Jürgens et al., 2019) presents an integrated reference model to show the influence of digitization on quality management. The paper was published in the IWI Discussion Paper Series. My role in this work was to support the development of the reference model and to provide general input for the paper. This paper is not considered further within this dissertation.

In addition to models and techniques for data analysis, general information about the installed base in manufacturing sites is required. The paper "Towards a Smart Services Enabling Information Architecture for Installed Base Management in Manufacturing" (Dreyer et al., 2017) presented at Wirtschaftsinformatik 2017 in St. Gallen, Switzerland presents an information architecture for installed-based management. This information architecture was developed following the ADR approach, and further design principles for such a system were presented. I was responsible for the research design and the applicability check of this work. Furthermore, I developed the architecture together with my coauthors and supported the development of the design principles. The previous research was extended by a comprehensive case study with a focus on predictive maintenance in the paper "Creating the foundation for digital twins in the manufacturing industry: an integrated installed base management system" (Olivotti, Dreyer, Lebek, et al., 2018), which was published in the Information Systems and e-Business Management journal. The writing of the paper was primarily my task, as was the elaboration of the research design. I developed the architecture in conjunction with the coauthors and finalized it independently. I was responsible for the test case presented in the paper and for the extension of the design principles from the information architecture work described above.

The manufacturing industry is increasingly being characterized by a combination of physical products and (virtual) services: so-called PSS. One approach to developing such PSS is presented in the paper "Modeling Framework for Integrated, Model-based Development of Product-Service Systems" (Apostolov et al., 2018), which presents a framework and applies it to the manufacturing environment. The paper was presented at the 10th CIRP Conference on Industrial Product-Service Systems (CIRP IPS2 2018) in Linköping, Sweden. The presented industrial case was my responsibility, and I also provided insights into concrete PSS in the paper. The shift from selling physical products to offering PSS requires new business models. This business model change can be accompanied by disruptive changes to the actual business. The paper "Realizing availability-oriented business models in the capital goods industry" (Olivotti, Dreyer, Patrick Kölsch, et al., 2018) gives insights into the realization of such business models for the capital goods industry with a focus on an industrial application. I presented the paper at the 10th CIRP Conference on Industrial Product-Service Systems (CIRP IPS2) 2018 in Linköping, Sweden. I was responsible for literature search and analysis. Further, I was the primary person responsible for the industrial application and the writing of the text. The offering of services has been common for many years now. Going a step further, smart services offer customer-oriented potential for new revenue channels. The paper "Focusing the customer through smart services: a literature review" (Dreyer, Olivotti, Lebek, et al., 2019) presents a broad literature review in the field of smart services. The paper was published in Electronic Markets in 2019. I participated in the detailed literature analysis of the paper as well as in the identification of research gaps for technologies and big data. Knowledge management receives special focus when offering smart services. The paper "Knowledge Management Systems' Design Principles for Smart Services" (Dreyer, Olivotti, and Breitner, 2019) was submitted to the BISE journal. I was responsible for working out the practical examples and use cases throughout the paper. I also participated in the development of the reference model and the conceptual development of the characteristics. Digital transformation is not only relevant to the production of industrial goods: purchasing is also influenced by digital transformation. A German research paper called "Digitalisierung im Einkauf: Eine Referenzarchitektur zur Veränderung von Organisation und Prozessen" (Stoll et al., 2018) described a reference architecture for the digital transformation of purchasing. Changes in organization and processes are analyzed and suggestions for practitioners provided. The paper was published in the IWI Discussion Paper Series. My part was to support the development of the architecture and the scientific results. This paper will not be considered further within this dissertation.

Another paper called “Assessing Research Projects: A Framework” (Passlick et al., 2018) proposes a framework to structure research ideas. The paper was also published in the IWI Discussion Paper Series. The framework was inspired by the business model canvas, and I developed it together with my coauthors and contributed to the discussion as well. This paper also will not be considered further within this dissertation.

Table 2: Overview of publications sorted by year and title

Year	Title	Authors	Outlet	WKWI[a]	JQ3[b]	IF[c]	SNIP[d]	Chapter	Appendix
2017	Towards a Smart Services Enabling Information Architecture for Installed Base Management in Manufacturing	S. Dreyer, D. Olivotti, B. Lebek and M.H. Breitner	Wirtschaftsinformatik 2017	A	C	-	-	Chapter 4	Appendix F
2018	Assessing Research Projects: A Framework	J. Passlick, S. Dreyer, D. Olivotti, B. Lebek and M.H. Breitner	IWI Discussion Paper Series	-	-	-	-	-	Appendix M
2018	Combining Machine Learning and Domain Experience: A Hybrid-Learning Monitor Approach for Industrial Machines	D. Olivotti, J. Passlick, A. Axjonow, D. Eilers and M.H. Breitner	Lecture Notes in Business Information Processing (LNBIP)	-	C	-	0.504	Chapter 3	Appendix C
2018	Digitalisierung im Einkauf: Eine Referenzarchitektur zur Veränderung von Organisation und Prozessen	I. Stoll, D. Olivotti and M.H. Breitner	IWI Discussion Paper Series		-	-	-	-	Appendix L
2018	Maintenance Planning Using Condition Monitoring Data	D. Olivotti, J. Passlick, S. Dreyer, B. Lebek and M.H. Breitner	Operations Research Proceedings 2017	-	D	-	-	Chapter 3	Appendix B
2018	Modeling Framework for Integrated, Model-based Development of Product-Service Systems	H. Apostolov, M. Fischer, D. Olivotti, S. Dreyer, M.H. Breitner and M. Eigner	Procedia CIRP	-	-	-	0.982	Chapter 5	Appendix H
2018	Optimizing Machine Spare Parts Inventory Using Condition Monitoring Data	S. Dreyer, J. Passlick, D. Olivotti, B. Lebek and M.H. Breitner	Operations Research Proceedings 2016	-	D	-	-	Chapter 3	Appendix A
2018	Realizing availability-oriented business models in the capital goods industry	D. Olivotti, S. Dreyer, P. Kölsch, C.F. Herder, M.H. Breitner and J. Aurich	Procedia CIRP	-	-	-	0.982	Chapter 5	Appendix K
2019	Creating the Foundation for Digital Twins in the Manufacturing Industry: An Integrated Installed Base Management System	D. Olivotti, S. Dreyer, B. Lebek and M.H. Breitner	Information Systems and E-Business Management (ISEB)	B	C	1.032	1.084	Chapter 4	Appendix G
2019	Einflüsse der Digitalisierung auf das Qualitätsmanagement und die Notwendigkeit einer integrierten Betrachtungsweise anhand eines Referenzmodells	L. Jürgens, D. Olivotti and M.H. Breitner	IWI Discussion Paper Series		-	-	-	-	Appendix E
2019	Focusing the customer through smart services: A literature review	S. Dreyer, D. Olivotti, B. Lebek and M.H. Breitner	Electronic Markets (EM)	A	B	3.818	1.269	Chapter 5	Appendix I
2019	Knowledge Management Systems' Design Principles for Smart Services	S. Dreyer, D. Olivotti and M.H. Breitner	Was submitted to: Business & Information Systems Engineering (BISE)	A	B	2,596	-	Chapter 5	Appendix J
2019	Predictive Maintenance as an Internet of Things enabled Business Model: Toward a Taxonomy	J. Passlick, S. Dreyer, D. Olivotti, L. Grützner and M.H. Breitner	Submitted to: Electronic Markets (EM)	A	B	3.818	1.269	Chapter 3	Appendix D

[a] Wissenschaftliche Kommission für Wirtschaftsinformatik 2008 WI-Orientierungslisten
[b] JOURQUAL3 Verband der Hochschullehrer für Betriebswirtschaft
[c] Thomson Reuters Impact Factor 2017
[d] Source Normalized Impact per Paper 2017

1 Introduction

„Every industry and every organization will have to transform itself in the next few years. What is coming at us is bigger than the original internet and you need to understand it, get on board with it and figure out how to transform your business.“

Tim O'Reilly, Founder and CEO, O'Reilly Media

1.1 Motivation and Problem Definition

Currently, the digital transformation is being discussed nearly everywhere. Digital transformation describes organizational changes that are enabled by or rely on the use of technologies (Nwankpa and Roumani, 2016); these technology trends are also summarized under the term "SMACIT", which stands for social, mobile, analytics, cloud and internet of things (Sebastian et al., 2017; Ross et al., 2016). Digital transformation is much more than simply using digital technologies or digitalize processes. It affects many sectors, such as banking and finance, insurance, the food industry and manufacturing. A shift in emphasis from traditional, nondigital businesses models to offering digital business models in addition or as a replacement has been recognized in the industry (Bock and Wiener, 2017). Increasing interest in digital business strategy is also being seen from researchers and practitioners (Markus and Loebbecke, 2013; Pagani, 2013; Nwankpa and Roumani, 2016). However, the process of implementing a digital transformation strategy is challenging and brings disruptive changes for people and organizations. According to Baiyere et al. (2017) many companies have difficulties with digital transformation in their organizations.

The digital transformation is also empowered by changing customer needs and greater requirements for flexibility as well as individuality. When digital technologies are used in companies, the question arises as to how they can be used to drive innovation and ensure competitiveness (Nwankpa and Roumani, 2016). Ross et al. (2016) see two main digital strategies, customer engagement and digitized solutions, which result in five recommendations for organizations to design and execute digital strategies: define a digital strategy; invest in an operational backbone—quickly; architect a digital service backbone; partner to acquire new skills and capabilities; and think services (Ross et al., 2016).

For the manufacturing industry, these disruptive changes have led to the PSS. Manufacturing companies are shifting from selling physical products to combining physical products with services. This type of offer is also called a digitized artifact, where physical assets are added by digital capabilities or value-added services (Herterich and Mikusz, 2016). Further, existing skills are enhanced by digital competencies (Ross et al., 2016), which allows high customer engagement, greater flexibility, and quick responses to changes in customer needs. So called smart services are customer-centric services mainly based on the usage of Information and Communications Technology (ICT) and high customer involvement. Particular interest is seen in the field of predictive maintenance. With the help of predictive maintenance and data analytics techniques and optimization models the probability machine breakdowns can be reduced. Based on predictive maintenance various business models are created or adjusted. Offering such predictive maintenance services requires an scalable and appropriate IT infrastructure. Not only detailed insights on sensor data or probability of default of a certain component is required but also context information. Combining context information and information from the whole product life cycle detailed digital representations, called digital twins, are possible. With the help of digital twins comprehensive insights for components, products and plants can be achieved.

To structure the topic of the digital transformation, this dissertation focuses on architectures with general applicability to the manufacturing industry. In addition to general architectures, new and relevant technologies for the digital transformation of the manufacturing industry are examined. This dissertation also discusses the implications for practitioners.

1.2 Structure of the Dissertation

This cumulative dissertation aims to contribute to the field of digital transformation in the manufacturing industry. Focus is therefore on technologies and architectures. The structure of the dissertation is shown in Figure 9.

Chapter 0 provides an overview of the publication underlying this dissertation. Along with the overview, a brief description of the task allocation is given to show what the author of this dissertation was responsible for in each paper. In Chapter 1, the motivation and problem definition underlying the research topics of this dissertation are provided and an overview is given of the structure of the dissertation. Chapter 2 provides the theoretical background on digital transformation in the manufacturing industry to ensure a common background. Chapters 3, 4 and 5 represent the main part of this dissertation. Chapter 3 addresses predictive maintenance applications for industrial machines. Herein, different models for optimizing spare parts and maintenance planning as well as approaches to predicting anomalies in machines are presented. Furthermore, a taxonomy for predictive maintenance is presented. In the second major section, Chapter 4, an integrated installed base management system and its relation to the concept of the digital twin are presented and discussed. Chapter 5 addresses PSS and business models for the capital goods industry. This chapter presents approaches to the development of PSS. A broad literature review of smart services is presented and knowledge management for smart services designs developed. Finally, the applicability of availability-oriented business models in the manufacturing industry is shown. In Chapter 6 an overall discussion of the research topic as well as limitations and directions for further research are given. The dissertation ends with an overall conclusion in Chapter 7.

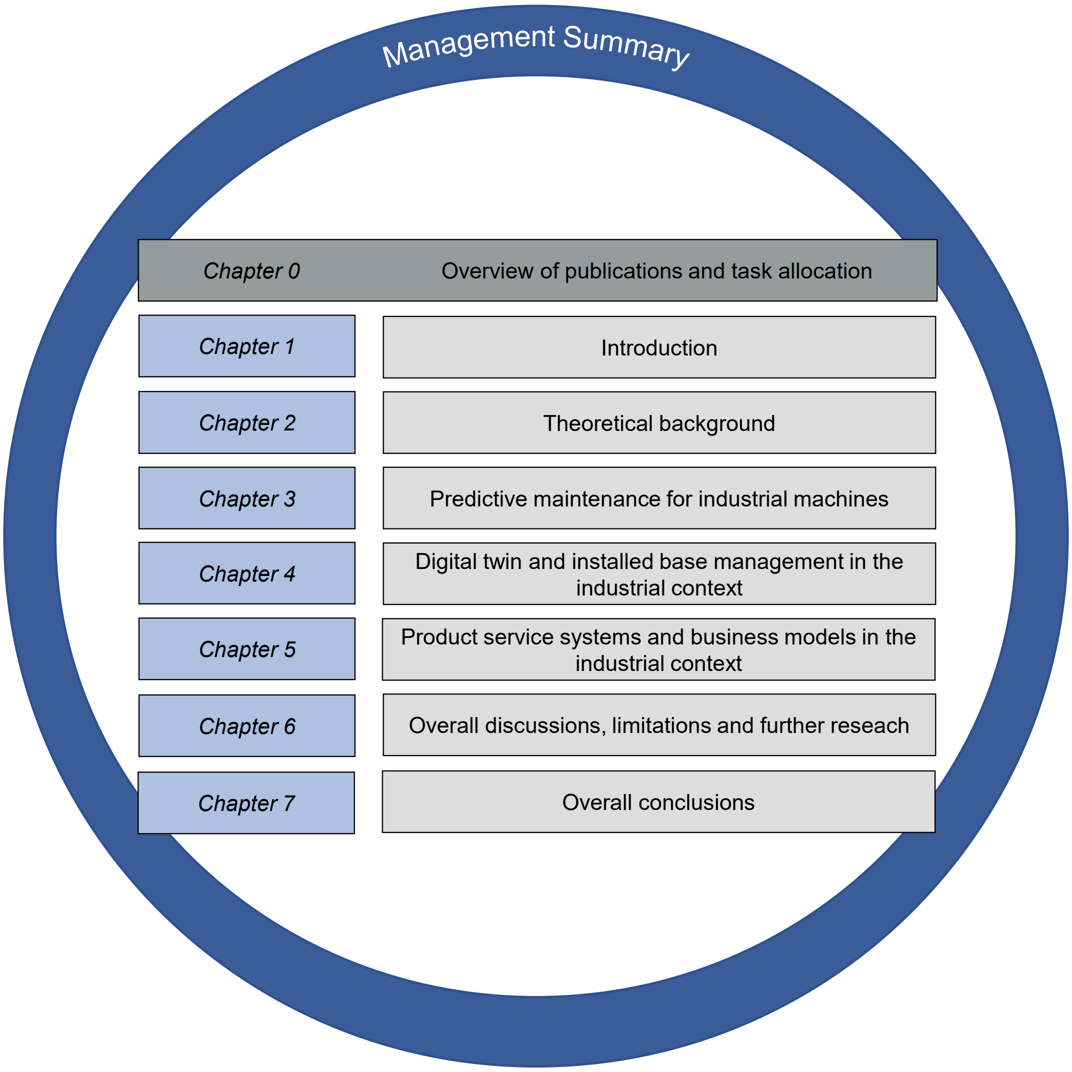

Figure 9: Structure of the dissertation

2 Theoretical background

2.1 From digitization to digital transformation

In fact the terms digitization, digitalization and digital transformation are not clearly distinguished by each other (Legner et al., 2017). Bockshecker et al. (2018) performed a literature to analyze the different terms in detail. Digitization is transforming analog content into digital content (Freitas Junior et al., 2016; Jackson, 2015). (Bockshecker et al., 2018) extends this definition by including also “the development of a digital infrastructure”. A rather technical focus of the term digitization is recognized (Legner et al., 2017). This means that the technical processing who to transform non digitial content into digital content is considered. Digitalization go a step further than digitization (Klötzer and Pflaum, 2017). According to Bockshecker et al. (2018) digitalization is “the state of an organization or a society referring to its current digital development and usage of ICT innovations”. Social and technical aspects need to be considered for digitalization (Bockshecker et al., 2018). Also Legner et al. (2017) emphasize the sociotechnial aspect of digitalization. Digitalization recognize the changes for organizations ind individuals by means of digitalization of products and processes. Digital transformation is a clear growth from the two terms mentioned before with the most impacts for organizations. The term digital transformation describe major changes for organizations and their business model causing a transformation by using digitalization or digital innovation (Osmundsen et al., 2018). This results in disruptive changes and resulting challenges for the organizations. Osmundsen et al. (2018) describe drivers and objectives why organizations face the digital transformation. They mention changing customer needs and changes in the competitors structure and partners. Therefore digital technologies and their applicability are investigated by companies in all industries (Matt et al., 2015). The usage of new technologies and changes in customer behaviour requires digital transformation of companies or whole industries. A digital transformation need to be well planned and a digital transformation strategy established to tackle the challenge with success.Matt et al. (2015) state out that a digital strategy is needed which differs from traditional IT strategies. Traditional IT strategies focus on IT infrastructures and backbones whereas digital transformation strategies set a focus on business impact and transformation of products and processes Matt et al. (2015).

2.2 Internet of Things and Industrial Internet of Things

The term Internet of Things (IoT) is a broad idea which is why there is no unique definition covering each aspect of the topic (Wortmann and Flüchter, 2015). The advantage of the IoT does not only lie in the digitization or digitalization itself, but in the received information and resulting service possibilities. When talking about the Internet, the topic of security and privacy arises. Considering that is necessary because security is a great challenge in the fast growing field of IoT. Legal requirements have to be met (M. Weber and Boban, 2016) as well as organizational policies and guidelines. Additionally the whole system has to be protected against access from outside. The IoT was mentioned the first time in the late 1990s by the Auto-ID Labs at Massachusetts Institute of Technology in the context of Radio-Frequency Identification (RFID) (Atzori et al., 2010; Wortmann and Flüchter, 2015). However, the idea of synchronizing technologies to create value in addition to the values of the individual objects (Högnelid and Kalling, 2015) does already exist more than 15 years.

In the industrial context the term Industrial Internet of Things (IIOT) is established nowadays. In general IIOT is the usage of IoT in manufacturing or industrial applications. An comprehensive definition of IIOT is provided by Boyes et al. (2018) as “A system comprising networked smart objects, cyber-physical assets, associated generic information technologies and optional cloud or edge computing platforms, which enable real-time, intelligent, and autonomous access, collection, analysis, communications, and exchange of process, product and/or service information, within the industrial environment, so as to optimise overall production value. This value may include; improving product or service delivery, boosting productivity, reducing labour costs, reducing energy consumption, and reducing the build-to-order cycle.” More than in the private sector a lot of different systems need to be considered as Cyber-Physical System (CPS). In the manufacturing industry also the term Cyber Manufacturing system is proposed (Jeschke et al., 2016).

2.3 Industrie 4.0

Related to the IoT, especially in Germany the term “Industrie 4.0” is widely known. Industrie 4.0 is a project established by the german Verband Deutscher Maschinen- und Anlagenbau (VDMA), Zentralverband Elektrotechnik- und Elektronikindustrie (ZVEI) und Bundesverband Informationswirtschaft, Telekommunikation und neue Medien e.V. (BITKOM) and part of the “Hightech-Strategie 2020” of the German federal goverment. The term is not only understood as a technology or an enabler for services. bus more as strategy. A suitable definition of Industrie 4.0 is the following quote from Lasi et al. (2014):

> "[...] it can be concluded that the term 'Industry 4.0' describes different – primarily IT driven – changes in manufacturing systems. These developments do not only have technological but furthermore versatile organizational implications. As a result, a change from product- to service-orientation even in traditional industries is expected."

The manufacturing systems are horizontally as well as vertically connected. From an internal point of view, they are connected with the business processes. Additionally, they are connected with other networks, going from the value chain to the value network. This change provides multiple possibilities to generate value. New business models can be developed and services in addition to the sold products can be offered, so called PSS. Hermann et al. (2016) name four Industrie 4.0 design principles: Interconnection, Information Transparency, Decentralized Decisions, and Technical Assistance. Their exists strong relation between Industrie 4.0 and IoT and IIOT but Industrie 4.0 focus more on a strategic level.

3 Predictive maintenance for industrial machines

3.1 Motivation

In the manufacturing industry, the usage of industrial machines is essential. These industrial machines are typically characterized by high investment costs and need to be highly available to ensure the planned output. High availability are ensured through the appropriate maintenance of these machines. In manufacturing companies, maintenance is a large cost factor (Bousdekis et al., 2015), and for decisionmakers, it can be challenging to find the right point in time to maintain industrial machines. Infrequent maintenance activities increase the probability of a machine breakdown and result in very high costs for repair and production losses, whereas too frequent maintenance activities can lead to unnecessary maintenance costs and machine downtime. To measure and track the effectiveness of an industrial machine, key figures such as the Overall Equipment Effectiveness (OEE) are considered.

Although the maintenance of industrial machines is relevant to ensure availability, it cannot entirely prevent a breakdown. Faults occur that are not predictable and not seen when performing maintenance actions. In such a case, faults can be counteracted by holding spare parts in stock or having them readily available. The inventory management of spare parts is a crucial factor in operations management (Aronis et al., 2004), and optimization models are thus applied to help calculate the optimal number of spare parts in stock based on the actual condition of the machine. An approach to calculating the optimal number of spare parts for a specific component is presented in the paper "Optimizing Machine Spare Parts Inventory Using Condition Monitoring Data" (Dreyer et al., 2018). Optimizing machine spare parts inventory means finding the right balance between spare parts costs and costs caused by machine downtime (Yang and Niu, 2009). The developed model minimizes costs by determining the optimal number of available spare parts. The costs are optimized for a specific type of component, specifically, a critical component for a machine that is used multiple times in the production site. This could, for example, be a certain motor or drive component. This approach makes it possible to reduce the number of spare parts held because the component can fit in several machines. The optimal number of spare parts is calculated based on the probability of default for each individual component, where the probability of default can be calculated based on empirical values and improved by data on the current state of a component as indicated by sensors. The components are utilized in heterogeneous machines and are not equally critical to the production process. This results in different potential downtime costs for each individual component based on the machine. The model is based on a new service concept that makes it possible to adjust the number of available spare parts in each period. In the newly developed service concept, the spare parts do not have to be bought, and instead, a lump-sum fee is charged for their provision. This lump-sum fee functions as a payment for the provision of a spare part. The advantage is that when a spare part is needed due to a component failure, it can be installed directly. When the optimal stock amount decreases, spare parts can be returned. Therefore, it is possible to decide how many spare parts should be available in each period to minimize the costs. A service provider can optimize its own stock of spare parts when serving different customers and thus can offer this type of flexible service to customers.

As stated earlier, maintenance is an important activity when operating industrial machines. Because predictive maintenance can help to predict machine faults, the question of when to maintain a machine arises. This question is even more important when several machines in a plant are considered and only brief time windows are available for maintenance due to the need to maintain full production capabilities. An intelligent maintenance policy is needed to manage this context. The paper "Maintenance Planning Using Condition Monitoring Data" (Olivotti, Passlick, Dreyer, et al., 2018) presents a decision support system, including an optimization model, to determine the optimal maintenance policy for several machines. Various influencing factors exist for such a maintenance policy. It is not sufficient to develop the optimal maintenance plan for a single machine, but the maintenance activities of several machines should be grouped on the same maintenance schedule (Bouvard et al., 2011), and sensor values could be used to support the grouping of machines. Especially when these machines are used in interchained production, grouping would help reduce setup and repair costs during maintenance (Wildeman et al., 1997). The use of sensor values to determine the actual state of a machine is a precondition for advanced condition-based maintenance (Peng et al., 2010). To support condition-based maintenance, the actual condition of the machine as determined by sensor data is included in the model, and a breakdown probability is calculated on the basis of several periods of data. Furthermore, the tradeoff between grouping machines to save setup and fixed costs and maintaining machines on a schedule that may not reflect the optimal timing is addressed.

In practice, not only the actual data for a machine are needed for condition-based maintenance but also prediction methods are required to forecast optimal maintenance activities (Kaiser and Gebraeel, 2009; Kothamasu et al., 2006). A meaningful approach is to ensure static maintenance intervals for condition-based maintenance or to predict maintenance. This approach leads to cost savings and a reduction in machine breakdown possibilities. To predict machine breakdowns, advanced data analytic techniques are necessary, particularly because the field of industrial machines is very broad. Machine builders face the challenge of building machines for different applications and requirements, particularly component suppliers, who produce components for a wide range of different machines. This means that it is challenging to develop suitable analysis models to predict a condition or failure. One possible approach is to combine machine learning and domain knowledge experience; this is presented within the paper "Combining Machine Learning and Domain Experience: A Hybrid-Learning Monitor Approach for Industrial Machines" (Olivotti, Passlick, Axjonow, et al., 2018). In PSS physical products or assets are combined with (digital) services (Neff et al., 2013; Oliva and Kallenberg, 2003; Schrödl, 2013). The developed hybrid-learning machine monitoring approach aims to combine the experiences of each party of a PSS. Such an approach should use different algorithms to process various sensor data and enable predictive maintenance services and better fault diagnoses. In addition, the main experts from the different partners (component suppliers, machine builders, machine operators) involved have substantial domain knowledge, which often also includes how different machines and components interact and is not limited to individual components or machines. Additionally, the information gained from productive operations is a valuable resource of knowledge.

Different applications and possibilities for looking at predictive maintenance from a technical view were described earlier. Predictive maintenance must also be considered from an economical point of view. It is not only used to ensure the productivity and availability of machines and components: new business models enabled by predictive maintenance technologies have gained increasing attention in the manufacturing industry. To structure predictive maintenance business models, a taxonomy for classification is presented in the paper "Predictive Maintenance as an Internet of Things enabled Business Model: Toward a Taxonomy" (Passlick et al., 2019). Business models of 113 companies are analyzed as described with the developed taxonomy. On that basis, six archetypes are developed and used to derive practical implications: hardware development, platform provider, all-in-one, information manager, consulting and analytics provider.

3.2 Theoretical background

3.2.1 Maintenance strategies

To understand the abovementioned models and approaches, it is necessary to understand different concepts of maintenance. Maintenance is not only a cost factor but also a strategic factor that can offer companies a competitive advantages (Faccio et al., 2014;

Waeyenbergh and Pintelon, 2002). Generally, maintenance is the "combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function" (D. I. N. Deutsches Institut für Normung e. V., 2018).

In the academic literature, maintenance strategies are classified mainly according to time. Basically two types of maintenance are distinguished: corrective and preventive (Wang et al., 2007). A single accepted definition of maintenance strategies does not exist in the academic community. An overview of different maintenance strategies is given in Figure 10. In this figure, predictive maintenance is separated from preventive maintenance to better show the evolution and importance of the former approach. According to DIN EN 13306:2018-02 (D. I. N. Deutsches Institut für Normung e. V., 2018) predictive maintenance is subordinated to condition-based maintenance.

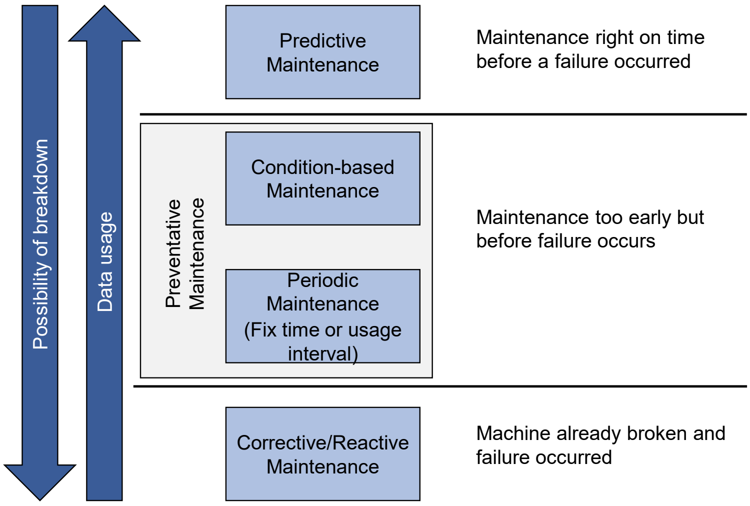

Figure 10: Overview of maintenance types

It is important to note that multiple maintenance strategies can coexist in a production plant. Based on the individual machine and its role in production, different maintenance strategies will be preferred. Even if predictive maintenance is the most promising approach to prevent machine breakdowns for certain applications, a corrective strategy can also make sense based on the number of identical machines and the occupancy rate. A machine can also be maintained through a combination of several maintenance strategies. For certain parts, a condition-based or predictive maintenance strategy can be established, whereas for other parts, only corrective actions are performed.

Corrective or reactive maintenance describes a strategy in which machines or components are repaired or replaced after a failure occurs. No actions are performed before this point in time to maintain the machine or components. When a failure occurs, a root-cause analysis must be performed to identify the defective parts. As the right spare part is not always in stock, long down times must be accepted.

Preventive maintenance intervenes before machine breakdown or failures occur. Two main streams of preventive maintenance can be seen. First, a fixed maintenance schedule or one based on predetermined conditions means that, for example, after 200 operating hours, certain components are replaced. A condition-based maintenance strategy is based on the real wear of machines or components, wear being tracked by sensor data. In this strategy, there is no prediction as to how the machine will behave in the future. This is where predictive maintenance comes along. Predictive maintenance can be seen as the highest level maintenance strategy (Susto et al., 2012). DIN EN 13306:2018-02 (D. I. N. Deutsches Institut für Normung e. V., 2018) defines predictive maintenance as "condition-based maintenance carried out following a forecast derived from repeated analysis or known characteristics and evaluation of the significant parameters of the degradation of the item". Therefore, data are also necessary for conducting predictive maintenance. Various prediction models and methods can be used based on the use case (Susto et al., 2012). To generate forecasts and predictions, for example, neuronal networks can be used.

3.2.2 Data analytics and neuronal networks

A predictive maintenance application is usually a data-driven approach that aims to find patterns during the operation of a machine that may indicate possible future failure. The data for such an approach can be collected by sensors. In addition to the already collected values for machines such as torque and current, additional sensors for vibration, noise and image recognition can be used to detect anomalies. Automatically finding patterns in these data streams is a task for machine learning. In machine learning, one can distinguish between supervised and unsupervised learning (Hastie et al., 2009). Supervised learning requires input data such as time series of the sensor values and a defined output such as a binary variable for machine failure or future states of the machine. Then, the model is trained to identify patterns in the input data, which leads to the defined output. Unsupervised techniques do not require labeled output data; these techniques attempt to find patterns in the data, for example, by clustering certain values together, which can then be analyzed further for possible reasons for machine failure. For predictive maintenance, one can use different approaches and combinations of such methods.

The most frequently used supervised approach is to collect time series data from machine sensors during normal operations and train a nonparametric machine learning model, which uses a specified data history as the input and future states of the machine as the output. Such a model fits itself to the expected behavior of the machine. A fully trained model can be used to compare the expected behavior of a machine with the actual behavior in real time. When the probability of an observed pattern occurring (based on an estimated normal distribution for general white noise deviations) is below a certain threshold, this can then be identified as an anomaly (Malhotra et al., 2015).

A typical unsupervised technique is to train a machine learning model to reconstruct the input values based on principal components. Therefore, input data such as a certain time window of sensor data is reduced to a smaller number of dimensions (the principal components), which are then used to reconstruct the original input values. This approach tries to identify the overall rules that lead to the observed patterns in the data. If a fully trained model is unable to reconstruct a pattern in new input data points, the rules from the past are no longer applicable. For anomaly detection, this means that a model that was trained on a machine behaving normally will produce high reconstruction errors if new patterns occur in the data, which may indicate an unusual or dangerous behavior (Sakurada and Yairi, 2014).

For both approaches, artificial neural network architectures exist. The supervised approach can be realized by Long Short-Term Memory (LSTM) neural networks (Hochreiter and Schmidhuber, 1997), which are trained on a certain time window to predict the value for the next time stamp. The unsupervised approach can be realized by autoencoders (Hinton and Salakhutdinov, 2006), which are also trained on a certain time window of sensor data, but with the goal of reconstructing these time series as exactly as possible based on the trained principal components.

3.3 Research design

The overall research design of this chapter is stated in Figure 11. At first, an optimization model to minimize the costs for spare parts provisioning is presented. The paper is called "Optimizing Machine Spare Parts Inventory Using Condition Monitoring Data" (Dreyer et al., 2018) and answers the RQ: How can the spare parts stock for industrial machines be optimized by the usage of condition monitoring data? A new service concept for the provisioning of spare parts is also presented. Building on this model and the service concept, a new model for the maintenance of industrial machines is created. Therefore, the paper "Maintenance Planning Using Condition Monitoring Data" (Olivotti, Passlick, Dreyer, et al., 2018) aims to answer the RQ: How can the spare parts stock for industrial machines be optimized by the usage of condition monitoring data? The two optimization models focusing on using condition monitoring data and show that data usage is indispensable, but insights from domain experts are required to interpret the data with their high domain knowledge and realize its value. For this purpose, the subsequent paper "Combining Machine Learning and Domain Experience: A Hybrid-Learning Monitor Approach for Industrial Machines" (Olivotti, Passlick, Axjonow, et al., 2018) presents a hybrid approach that combines machine learning and domain knowledge. This paper aims in answering the RQ: How can machine learning and domain knowledge be combined to support predictive maintenance applications of industrial machines?. A general framework is proposed that consists of three modules, and an applicability check within an automation and engineering company is performed for one of the modules. Previous research also shows that predictive maintenance is a promising approach in the manufacturing industry. However, it is also seen that various predictive maintenance technologies and business models exist. The paper "Predictive Maintenance as an Internet of Things enabled Business Model: Toward a Taxonomy" (Passlick et al., 2019) presents a taxonomy to classify predictive maintenance business models and to suggest implications for practice in order to enable new business models or adjust existing ones. The paper The paper is based on the following, underlying RQ: Which elements of predictive maintenance business models are important and which characteristics are interrelated on the market?.

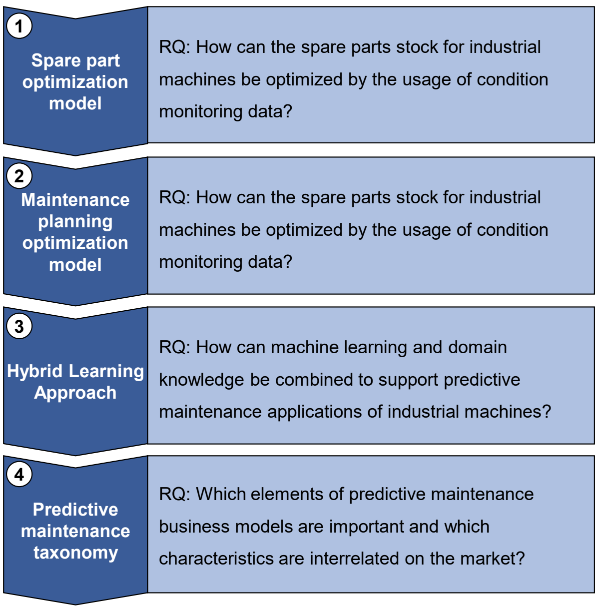

Figure 11: Research design overview - Predictive maintenance

3.4 Models and findings

3.4.1 Spare part maintenance

The paper “Optimizing Machine Spare Parts Inventory Using Condition Monitoring Data” (Dreyer et al., 2018) presents a model to estimate the optimal number of spare parts in stock. For machine operators, it is essential to have the right number of spare parts in stock. Too few spare parts increases downtimes and results in lost production. A high number of spare parts results in occupied storage space and costs for the spare part.

Figure 12 shows the general procedure to determine the optimal number of spare parts.

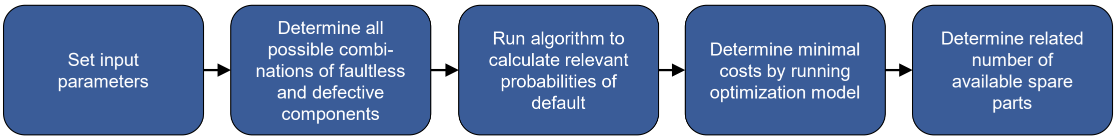

Figure 12: General procedure to determine the optimal number of available spare parts

The sum of provision costs for spare parts and potential downtime costs is minimized and results in the optimal number of spare parts per period. An assumption of the model is that at the end of each period, a check is performed to determine if components are defective or not. Consequently, within a period, the repair of components with high downtime costs is prioritized. The components are sorted according to the machine downtime costs associated with their use. The probability of default for a component can be calculated by condition-based sensor data, empirical values or even a combination of both. For technical components, a Weibull distribution can typically be assumed along the lifetime of a component (Jin and Liao, 2009; Louit et al., 2011). With the help of a decision tree, all possible combinations of error-free and broken components are calculated. The number of branches corresponds to $b = 2^c$ where c is the total number of components. (Dreyer et al., 2018)

The optimization model for the optimal number of spare parts (Dreyer et al., 2018):

Sets:

$i = (1,\ ...,\ c)$:	considered component of in total c components where $i = 1$ is the component which causes the highest downtime costs
$j = (1,\ ...,\ b)$:	considered branch of in total b branches
$k = (0,\ ...,\ c-1)$:	possible number of available spare parts

Parameters:

Cd_i:	downtime costs of the machine with the installed component i
Cp:	provision costs for one spare part
e_i:	effect on the machine breakdown
p_{ik}:	probability of downtime costs; *determined by algorithm*
pd_i:	total probability of default
pe_i:	probability of default resulting from empirical values
ps_i:	probability of default resulting from sensor data
w:	weighting of probability resulting from sensor data
cs_{ij}:	0, if component status is faultless, 1 else
q_{ij}:	probability of component within the branch pd_i, if cs_{ij} is 1, $1 - pd_i$ else; *with* pd_i *from (4)*
y_{ijk}:	1, if downtime costs have to be paid, 0 else

Decision variable:

x:	number of available spare parts

$$Min\ f(x) = \begin{cases} x \times Cp + \sum_{i=x+1}^{c} p_{ix} \times Cd_i \times e_i & \forall\ x < c \\ x \times Cp & x = c \end{cases} \tag{1}$$

$$0 \leq x \leq c \qquad x \in \mathbb{N}_0 \tag{2}$$

$$0 \leq e_i \leq 1 \qquad \forall\ i \tag{3}$$

$$pd_i = w \times ps_i + (1 - w) \times pe_i \qquad \forall\ i \tag{4}$$

$$0 \leq p_{ik}, pd_i, pe_i, ps_i \leq 1 \tag{5}$$

$$0 \leq w \leq 1 \tag{6}$$

$$cs_{ij} \in \{0, 1\} \qquad \forall\ i\ and\ j \tag{7}$$

$$y_{ijk} \in \{0, 1\} \qquad \forall\ i,\ j\ and\ k \tag{8}$$

$$b,\ c \in \mathbb{N} \setminus \{0\} \tag{9}$$

The objective function (1) is used to minimize costs. These cost are the sum of the provision costs for components and the expected downtime costs of a machine caused by a component. It is assumed that the number of spare parts must not exceed the number of installed components, and no negative numbers are allowed for spare parts (2). After each period, the number of spare parts can be adjusted, so that spare parts that have been installed as components are no longer counted. To capture the importance of a component in a machine, the effect of the component on machine downtime must be between zero and one (3), where zero means there is no effect on the machine, and one means there is a complete machine breakdown when the component is defective. The probability of default for a component is determined by sensor data as well as empirical values and can be weighted as desired (4); however, the probabilities of default must be between zero and one (5)and the weighting factor must also be between zero (considering only empirical values) and one (considering only sensor data) (6). The decision tree indicates if a component is faultless (0) or defective (1) (7). A binary variable is also used to describe whether there are downtime costs for a component (1) to be paid or not (0) (8). This combinations are determined by the developed algorithm. Finally, the number of branches and components must be from the set of natural numbers (9). (Dreyer et al., 2018)

The probability of downtime costs p_{ik} must be determined for each possible combination of spare parts based on the installed components. This is done separately by an algorithm, and it is assumed that $k < i$ to reduce combinations.

(step 1) Set $i = 1$, $j = 1$ and $k = 0$.
(step 2) If $cs_{ij} = 0$, set $y_{ijk} = 0$.
(step 3) Else: If $\sum_{a_1=1}^{i} cs_{a_1 j} \leq k$, set $y_{ijk} = 0$.
(step 4) Else set $y_{ijk} = 1$.
(step 5) Increment j by 1. If $j \leq 2^c$, go to (step 2).
(step 6) Else calculate $p_{ik} = \sum_{a_3=1}^{b}(y_{ia_3k} \times \prod_{a_2=1}^{c} q_{a_2 a_3})$.
(step 7) Increment i by 1. If $i \leq c$, set $j = 1$ and go to (step 2).
(step 8) Else increment k by 1. If $k < c$, set $i = k + 1$ and $j = 1$ and go to (step 2).
(step 9) Else terminate.

The number of spare parts is set to zero (step 1) and the component with the largest downtime cost is established. First, the first branch is considered. Step 2, step 3 and step 4 check whether a component is defective or faultless and whether downtime costs occur or if enough spare parts are in stock. A descending sort based on machine downtime costs prioritizes the components that will be replaced by spare parts, and this sort is subsequently performed for each branch (step 5). For each component, the probability of downtime costs is calculated (step 6), and then this is repeated for the next component (step 7). This process is then repeated for the first branch. The number of available spare parts is then incremented by one (step 8). The procedure starts at the beginning until the maximum number of available spare parts is reached (step 9). The resulting probabilities of downtime costs p_{ik} are used to solve the objective function (1) of the optimization model. (Dreyer et al., 2018)

The following experimental results are based on the presented optimization model and algorithm. A test case with 10 components is used to show some results from the models. The input parameters are presented in Table 3.

Table 3: Input data for the test case

Number of installed components	**Provision costs for one spare part**	**Weighting of probability resulting from sensor data**
10	varied	50 %

Component	**Machine**	**Downtime costs of the machine**	**Probability of default (sensor data)**	**Probability of default (empirical values)**	**Effect on machine breakdown**
1	1	20000	0.02	0.01	0.8
2	1	20000	0.06	0.05	0.8
3	2	30000	0.20	0.07	0.8
4	2	30000	0.08	0.70	0.7
5	3	15000	0.09	0.11	0.5
6	3	15000	0.80	0.13	0.3
7	4	35000	0.11	0.05	1.0
8	4	35000	0.12	0.17	0.2
9	5	25000	0.13	0.11	0.6
10	5	25000	0.14	0.21	0.9

In this test case, only the provision costs for components are varied, and all other input data are not changed. Figure 13 shows the influence of the provision costs on the optimal number of spare parts.

The provision costs used are 50, 1,500, 5,000 and 10,000, and the curve has the same shape for each of the used provision costs. The provision costs have a relevant impact on total costs and on the the optimal number of spare parts. This is especially relevant for service providers who need to calculate their provision rate.

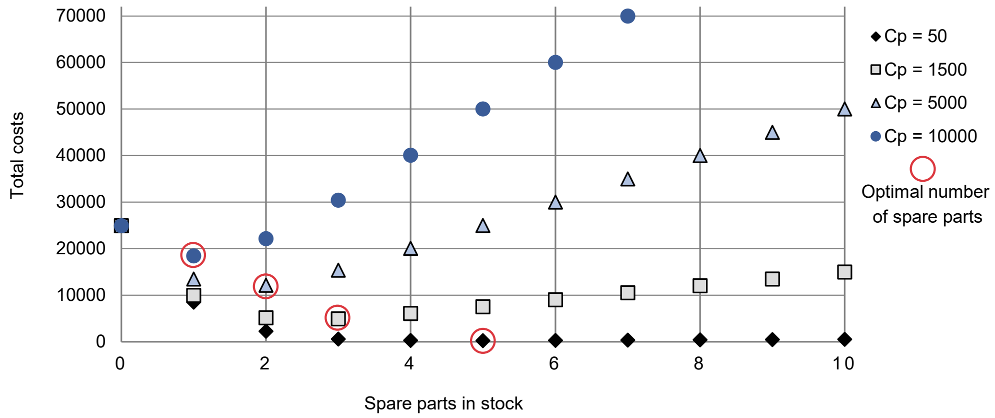

Figure 13: Comparison of different provision costs in relation to the number of available spare parts

3.4.2 Maintenance planning

The paper "Maintenance Planning Using Condition Monitoring Data" (Olivotti, Passlick, Dreyer, et al., 2018) presents a decision support system for determining the optimal maintenance policy based on the actual condition of the machine. The goal is to determine the optimally grouped maintenance activities as influenced by the costs of maintenance and the costs of a possible breakdown. The general procedure for this approach is shown in Figure 14. In the first step, the relevant input parameters are set for the model. Herein,

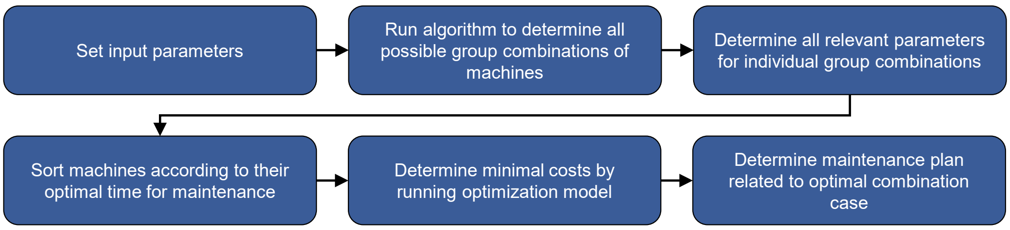

Figure 14: General procedure to determine the optimal maintenance activities

only machines that need to be maintained in the considered timeframe are included. The number of machines influences the potential grouping possibilities. It is assumed that general costs for maintenance apply that are not machine specific but relevant for a group of machines, for example, general setup costs for maintenance activities. For all machines, the probability of failure in future periods and the resulting breakdown costs are also input variables. The probability values can be estimated through a function such as a Weibull distribution or by other models for each period. Subsequently, an algorithm determines all possible group combinations, and machines with similar individual optimal maintenance times are grouped. The number of different possible combinations is 2^{M-1}, with M being the number of machines. Prior to the execution of the optimization model, the machines are sorted in ascending order based on their optimal maintenance date. The objective of the optimization model is to minimize the maintenance costs and costs for potential group cases while providing the optimal group combination for maintenance. Finally, a maintenance plan with the maintenance times for each machine in the group combination case is defined. (Olivotti, Passlick, Dreyer, et al., 2018)

Sets:

$i = (1, ..., 2^{M-1})$: Considered combination case

$j_i = (1,\ ...,\ g_i)$: Considered group in combination case i

$m = (1,\ ...,\ M)$: Considered machine with M: total number of machines

$t = (0,\ ...,\ T)$: Considered period with T: number of periods in the future

Parameters:

C_{j_i}: Total costs of a group j in a combination case i

D_m: Downtime costs of the machine m

F: Maintenance costs per group

g_i: Number of groups in a combination case i

n_{j_i}: Number of machines in a group j in a combination case i

p_{mt}: Probability of failure for machine m in period t

V_m: Maintenance costs for machine m

x_{j_i}: Smallest machine number in a group j in a combination case i

$$\min\left\{\sum_{j_i=1}^{g_i} C_{j_i} + g_i \times F \,\middle|\, i = 1, \dots, 2^{M-1}\right\} \tag{10}$$

$$C_{j_i} = \min\left\{\sum_{m=x_{j_i}}^{n_{j_i}+x_{j_i}-1} \left| D_m \times p_{mt} - \frac{F}{n_{j_i}} - V_m \right| \middle| t = 0, \dots, T\right\} \tag{11}$$

$$0 \leq p_{mt} \leq 1 \qquad \forall\, m \text{ and } t \tag{12}$$

$$p_{m(t-1)} \leq p_{mt} \qquad \forall\, m \text{ and } t \tag{13}$$

$$\frac{F}{n_{j_i}} + V_m \leq D_m \qquad \forall\, j_i \text{ and } m \tag{14}$$

$$V_m, F \geq 0 \qquad \forall\, m \tag{15}$$

$$1 \leq j_i \leq M \qquad \forall\, i \tag{16}$$

$$1 \leq x_{j_i} \leq M \qquad \forall\, j_i \tag{17}$$

$$g_i,\ n_{j_i},\ x_{j_i} \in \mathbb{N} \setminus \{0\} \tag{18}$$

$$M,\ T \in \mathbb{N} \setminus \{0\} \tag{19}$$

The main goal is to minimize costs for maintenance activities over all possible combinations (10). The total costs include the costs for each group in a combination plus the fixing costs for each group. Minimizing these costs results in the combination with the lowest costs. The costs for each group in a combination are defined in (11) and are calculated as the difference between expected downtime costs and costs for machine maintenance activities. The costs for maintenance are the sum of the individual machine maintenance costs and general maintenance costs for the group. To allocate these general group maintenance costs to each machine, the cost is divided by the number of machines in a specific group and that portion is assigned to each machine. The parameters n_{j_i} and x_{j_i} are defined considering the possible group combinations. The probability of failure is between zero (brand new machine) and 1 (broken machine) (12). It is further assumed that the probabilities are given for the relevant periods, e.g., by prediction models. It is also assumed that a machine can only degrade and that the probability of failure can only be reduced while performing maintenance activities (13). To show the impact of the downtime costs of a machine, these costs must always be greater or equal to the maintenance costs of the machine (14). Maintenance costs per machine and group must be positive, as ensured by (15). Constraints (16) and (17) ensure that j_i and x_{j_i} are equal or less than the number of machines. The number of machines, periods, groups in a combination, and machines in a group and the smallest number of machines in a group are defined as positive integers (18) (19). (Olivotti, Passlick, Dreyer, et al., 2018)

A demonstration case is used to show the applicability of the presented decision support system, including the optimization model. The general input parameters are stated in Table 4. These input parameters are independent from any specific period and are applied generally in the model. The probabilities of failure used for future periods are shown in Table 5. No input parameters vary except for the maintenance costs per group. The goal is to determine how the maintenance costs per group influence the number of groups. Figure 15 shows the results of the demonstration test case and the optimal number of groups, which depends on the maintenance costs per group. It is obvious that as maintenance costs for a group increase, the number of groups formed is usually reduced. The results also show that for specific maintenance costs per group, the number of groups can decrease and then rise again. Therefore, there are two main effects. First, if there are machines with proximate optimal times for maintenance, the grouping has stronger effects. This can be seen in Figure 15 for low maintenance costs per group, where a jump in the number of groups from five to three occurs. The second effect is caused by a higher number of machines in a group, which leads to lower proportionate group maintenance costs for each machine. (Olivotti, Passlick, Dreyer, et al., 2018)

Table 4: Maintenance costs and downtime costs for each machine

Number of machines	**periods**	**Maintenance costs for a group**
8	10	varied

Machine	**Maintenance costs**	**Downtime costs**
1	600	1,000
2	1,500	5,000
3	1,200	2,000
4	800	1,600
5	450	1,150
6	1,050	1,200
7	950	2,400
8	650	8,000

Table 5: Probability of failure for machines and periods

Period	**Machine**							
	1	2	3	4	5	6	7	8
0	0.01	0.03	0.01	0.01	0.28	0.15	0.02	0.02
1	0.01	0.04	0.02	0.05	0.31	0.23	0.05	0.08
2	0.02	0.07	0.52	0.07	0.41	0.29	0.21	0.16
3	0.03	0.10	0.61	0.09	0.52	0.32	0.36	0.28
4	0.15	0.20	0.63	0.15	0.56	0.38	0.39	0.34
5	0.26	0.33	0.67	0.23	0.60	0.41	0.43	0.39
6	0.39	0.50	0.69	0.25	0.63	0.45	0.48	0.41
7	0.65	0.60	0.70	0.25	0.69	0.56	0.51	0.49
8	0.74	0.75	0.75	0.48	0.72	0.59	0.56	0.57
9	0.81	0.78	0.78	0.59	0.80	0.82	0.66	0.62
10	0.92	0.83	0.80	0.72	0.92	0.96	0.70	0.75

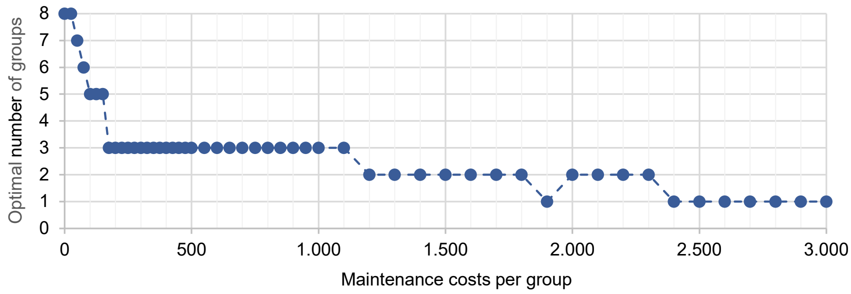

Figure 15: Different costs per group in relation to the number of groups

The presented model does not consider how many periods from the individual optimum time the group maintenance has been scheduled. However, the difference between maintenance costs and expected breakdown costs are relevant for each period. A strong influence of the degradation progress of a machine is observed in this cost difference. Because the absolute value is used, it can shift the maintenance time of a machine forward or backward. This results in a wide range of group combinations.

3.4.3 Hybrid-learning machine monitoring approach

The paper "Combining Machine Learning and Domain Experience: A Hybrid-Learning Monitor Approach for Industrial Machines" (Olivotti, Passlick, Axjonow, et al., 2018) presents a hybrid-learning machine monitoring approach for industrial machines. The approach consists of three interactive modules. Figure 16 provides an overview of the developed architecture.

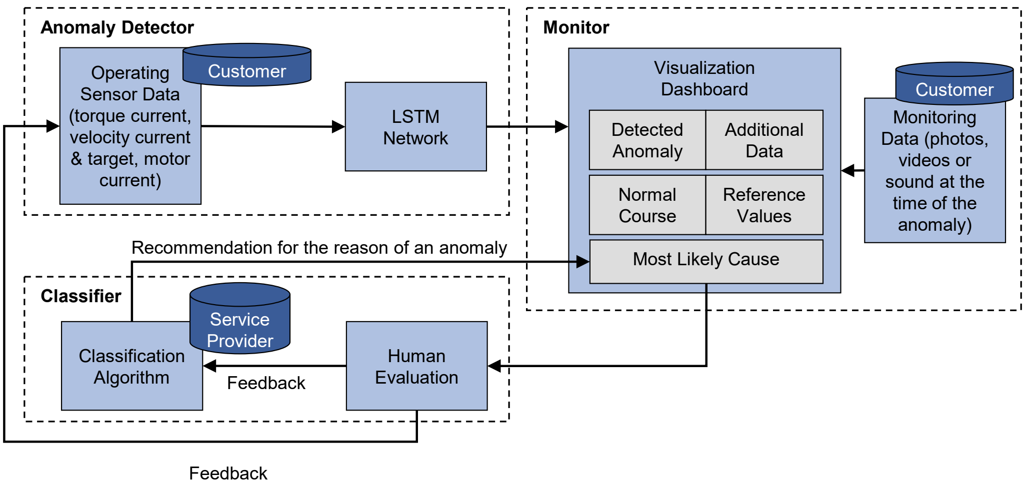

Figure 16: The developed machine monitoring approach

The first module is used for detecting anomalies in components and industrial machines based on operational data. These operation data can be high-frequency data, such as motor torque or current, and are based on the operating status of the machine. When machines operate, similar repetitive patterns can be observed, but depending on the application of the machines, these patterns can also differ. For example, a conveyor belt at an airport is used to transport different pieces of luggage with different dimensions and weights. Anomalies are detected by deviations from the expected time series. The approach to detecting anomalies that is used in this case is LSTM. The concept of hybrid-learning machine monitoring approaches is generally applicable, and so, based on individual applications, other methods are suitable for detecting anomalies.

In the first module, an anomaly is detected. In the case of a detected anomaly, the monitor module is triggered. It is important to solve the problem that causes the anomaly, and so this module should help the operator or engineer to identify the root cause of the anomaly to help to prevent the machine from incurring expensive breakdown costs or to reduce its downtime. The core component is a visualization dashboard that shows a visual representation of the detected time series anomaly. Additionally, time series without failure are provided for comparison purposes. Multiple data sources are used in this module to suggest for the domain different possibilities to look into. In particular, data that are not used to detect the anomaly but can be relevant to root-cause analysis are shown. These can also include audio or video sequences as well as other sensor data from a machine or component.

The classifier module supports the identification of causes for a specific anomaly. When an anomaly is detected, the classifier module obtains all available data to determine which is the most likely cause. For all possible causes, a probability is calculated, and a recommendation based on the probability is given to the monitor module, which is the central interface for the domain expert. It is important that after identifying the real cause, feedback is given to the system by the domain expert or a machine operator, as this indirect feedback will increase the quality of the model step by step. Additionally, when an anomaly occurs and the cause is not known, the data are included in the database. This is always done for false positive notifications, screened by an expert, to improve normal operation behaviors. In the case of a true positive from the anomaly detector model but an incorrect classification of the cause, two cases can result. In the first case, the anomaly is known but mismatched. Here, manual labeling by the domain expert is performed. In the second case, the anomaly is detected for the first time and was not previously known. Here, a new class must be defined by the domain expert to improve the model. When initially setting up the Decision Support System (DSS), it is suggested that domain experts classify all detected anomalies, including anomalies that are classified correctly with a high probability. This process ensures quality improvement of the model and further progress in its automation. This iterative approach aims at the continuous improvement of the model and the root causes analysis. Anomaly detection is only one part of the presented hybrid learning approach for industrial machines. Different approaches to anomaly detection exist for different use cases. One example of an approach that is realized with an industrial partner is described briefly in the next section of this dissertation. For a more detailed description, see the full paper “Combining Machine Learning and Domain Experience: A Hybrid-Learning Monitor Approach for Industrial Machines” (Olivotti, Passlick, Axjonow, et al., 2018).

Different cases were realized with the industry partner Lenze, a German manufacturer of automation solutions. Their products and automation solutions are used in automotive, robotics, packaging and materials handling applications, and their main components are motors, gearboxes, inverters and controllers. The module for anomaly detection was already implemented and evaluated for the mentioned industrial partner, but the other modules have not been implemented to date, and only a conceptual approach has been taken. A demonstration machine was used to develop the anomaly classification with LSTM. This demonstration machine shows a typical application of the automation solutions from Lenze. It consists of three consecutive conveyor belt modules. These conveyor belts are used to move various goods, e.g., cargo, baggage or parcels. Nearly 600,000 time series windows for normal operations were created for various load situations. For anomaly detection, the torque time series was identified as the most valuable and provided insights into the machine’s operating status. For a detailed description of how the anomaly detector module was initialized, please follow Olivotti, Passlick, Axjonow, et al. (2018). To visualize the results of the model Figure 17 shows the normal operation of a machine (left) and an illustration of a detected anomaly (right). This anomaly can occur due to insufficient motor bias, where, as a consequence, a slip between the toothed belt and the shaft of the asynchronous motor occurs. An evaluation with 208 test runs was performed on the demonstration machine, where a total of 153 test runs contains a simulated anomaly, and 55 test runs have normal operations and no simulated anomaly. Table 6 shows the respective confusion matrix. The results show an accuracy rate of 90.9%, a true positive rate (correctly identified anomalies) of 91.5% and a false positive rate (false alarm) of 10.9% in the current setting. (Olivotti, Passlick, Axjonow, et al., 2018)

Table 6: Confusion matrix

	no anomaly	anomaly
predict no anomaly	49	13
predict anomaly	6	140

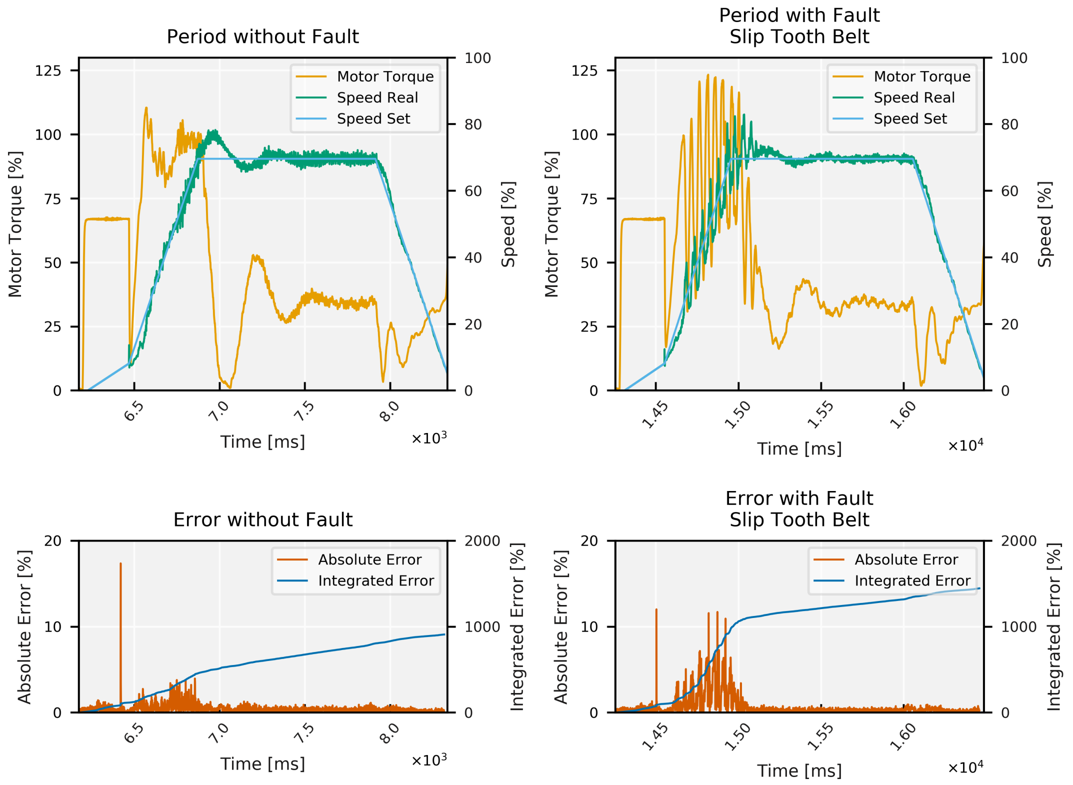

Figure 17: Normal operation scenario vs. detected anomaly

3.4.4 Predictive maintenance business models taxonomy

The paper “Predictive Maintenance as an Internet of Things enabled Business Model: Toward a Taxonomy” (Passlick et al., 2019) describes a taxonomy for predictive maintenance business models. This taxonomy aims to identify which elements are predictive maintenance business models are important and combined in practice. The taxonomy was developed according to a research procedure by Nickerson et al. (2013), which is shown in Figure 18. According to Nickerson et al. (2013) a taxonomy is “a set of it n dimension $Di(i = 1, ..., n)$ each consisting of $ki(ki > 2)$ mutually exclusive and collectively exhaustive characteristics [...]” (Nickerson et al., 2013, p. 340). At the beginning of the research process meta-characteristics are defined. They are an abstract description of the area of interest of the intended taxonomy. For the presented research, the meta-characteristics are chosen as definitions of the elements of predictive maintenance business models. The key element of the procedure by Nickerson et al. (2013) is that the taxonomy is developed in several iterations. For each iteration, either an empirical-to-conceptual or conceptual-to-empirical approach can be chosen. At the end of each iteration, it is determined whether the end condition is met and a further iteration is necessary. The end condition from Nickerson et al. (2013) was adapted and can be found in the mentioned paper (Passlick et al., 2019).

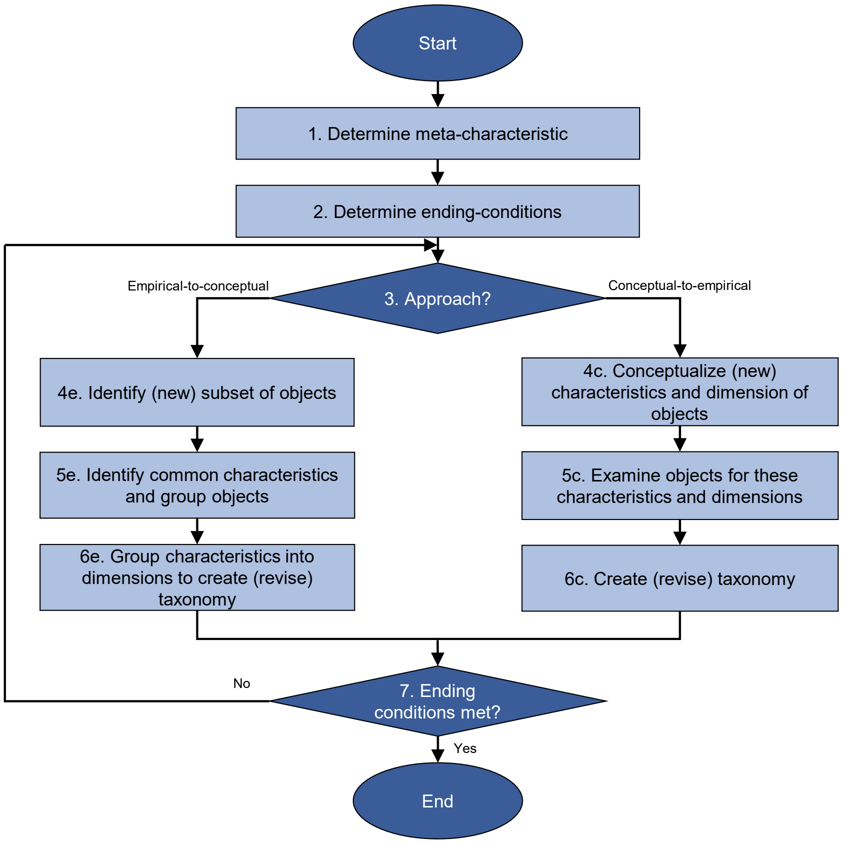

Figure 18: Taxonomy development procedure by Nickerson et al. (2013)

The first iteration is driven by a conceptual-to empirical approach. Therefore, the literature on business models was examined, and key terms were identified. The business model canvas by Osterwalder and Pigneur (2010) established the basis for the identified elements of the business models and our taxonomy. In the second iteration, an empirical-to-conceptual approach was used, and real-world predictive maintenance business models were analyzed. A total of 42 interviews at the 2018 Hannover Messe fair were conducted based on the results of the first iteration. Additionally, companies with a connection to predictive maintenance were identified by a Google search and a search in the Crunchbase website, which led to a dataset containing 113 companies. Ten randomly chosen companies were used to derive characteristics and further improve the taxonomy. In the third iteration, empirical-to-conceptual, a set of 20 random companies (not containing the previously used 10 companies) was used to check if the previous derived dimensions and characteristics were suitable. Additional changes to the taxonomy were also performed in this step based on the analyzed companies. In the next step, 30 more companies were analyzed, and some characteristics were added to the company. After the fourth iteration, the remaining 53 companies were examined, and no further changes were made; the end conditions of the taxonomy development were fully filled. (Passlick et al., 2019)

The final taxonomy is shown in Table 7, which presents the worked-out dimensions and characteristics. The first dimension described the key activities performed by a company, which results in various characteristics. For example, a firm could be engaged in the provision of certain hardware or software development, consulting services or universal activities. Value promise describes how customers' problems are solved and needs satisfied (Osterwalder and Pigneur, 2010).

Table 7: Developed taxonomy

Dimensions	Characteristics	
Key activities	1) Hardware development 2) Software development 3) Consulting 4) Edge computer development	5) Provision of a public cloud 6) Hardware retailer 7) Universal range 8) Provision of an application platform
Value promise	1) All-in-one solution 2) Condition monitoring 3) Connectivity 4) Automation	5) Forecasting 6) Data security 7) Data storage + software development tools
Payment model	1) One-time sales 2) Time basis 3) Project	4) Usage basis 5) Hybrid
Deployment channel	1) Physically 2) www 3) Physically + www (cloud)	4) www (cloud) + API 5) www (cloud) 6) Physically + www (cloud) + API
Customer segment	1) Manufacturing industry 2) Energy sector 3) No industry focus	4) High-security areas 5) Manu. industry + energy sector 6) Manu. industry + Logistics/Transport Industry
Clients	1) B2B 2) B2B + B2B2B	3) B2B + state
Information layer	1) Application and services 2) Information handling 3) Information delivering layer	4) Object sensing and information gathering layer 5) Multiple

Here, companies can either have an all-in-one solution or are specialized on certain topics such as automation or forecasting. Payment models can be a one-time payment for a defined output or regular usage or time-based. A combination of the previously mentioned characteristics is also possible. The dimension deployment channels describe how the company provides their product or service to their customers. Existing companies focus on a certain customer segment, such as manufacturing industries or the energy sector, or companies have no special industry focus; this is represented in the customer segment dimension. The customer segment dimension has a strong relation to the client dimension, which describes the types of customers in focus. The last dimension is the information layer, and it describes the way in which information and services are provided to the customer. Detailed definitions of each category can be found in the Appendix of "Predictive

Maintenance as an Internet of Things enabled Business Model: Toward a Taxonomy" (Passlick et al., 2019).

All companies were assigned to the characteristics of the taxonomy to show its applicability. To provide an overview of the predictive maintenance market and the companies, we have defined six archetypes. This procedure is used in other development processes for taxonomies as well (Gimpel et al., 2017; Eickhoff et al., 2017). In a first step, we used the clustering algorithm according to Ward (1963) in combination with the Sokal and Michener (1985) matching coefficient as a distant measure. The result gave us six groups, and we labeled them as follows: consulting, hardware development, platform provider, information manager, analytics provider, and all-in-one. Using an approach based on Hartmann et al. (2016), we clustered using the k-means and k-medoids algorithms. The k-medoid algorithm provides better results and results in a clear differentiation of the formed groups with assigned key activities. Detailed results of the cluster analysis are also provided in the paper by Passlick et al. (2019). Based on the identified clusters the archetypes with their key activities were defined and are stated in Table 8. To better inter-

Table 8: Predictive maintenance business model archetypes

	Archetype 1	**Archetype 2**	**Archetype 3**	**Archetype 4**	**Archetype 5**	**Archetype 6**
Label	Hardware development	Platform provider	All-in-one	Information manager	Consulting	Analytics provider
Key activities	Hardware development	Provision of an application platform	Universal offer	Edge computer development	Consulting	Software development
Value promise	Condition monitoring	Forecasting	All-in-one solution	Condition monitoring	Condition monitoring	Forecasting
Payment model	One-time sales	Hybrid	Hybrid	Hybrid	Project	Time basis
Deployment channel	Physically	Physically + www (cloud)	Physically + www (cloud)	Physically + www (cloud)	Physically	www (cloud)
Customer segment	No industry focus	Manufacturing industry	No industry focus	Manufacturing Industry	No industry focus	No industry focus
Clients	B2B	B2B	B2B	B2B + B2B2B	B2B	B2B
Information layer	Object sensing and information gathering	Application and services	Multiple	Multiple & information delivering	Application and services	Application and services & information handling
Share in sample (113)*	21%	12%	27%	5%	13%	20%
Example company	Rockwell Automation	Test Motors	National Instruments	IXON	Hitachi Consulting	Senseye

*Due to rounding inaccuracy the sum is not exactly 100%

pret the results graphically, we visualized the results in a two-dimensional grid. The two-dimensional representation of all assigned characteristics is achieved by a dimensionality reduction technique using an autoencoder. Herein, dependencies and possible nonlinear relationships between the characteristics are combined, and all characteristics are used as input features. The visualization is shown in Figure 19. Each dot represents a firm with a corresponding color, where the color matches the k-medois clustering (archetypes). In Figure 19, three main areas can be identified. This graphical representation was further used to find correlations and explanations for the clustering. For example, companies associated with "all-in-one" are represented in all areas. This matched the definition and emphasizes that this group has no special focus. This group is mainly distinguished from other groups by the key activities and value promise dimensions. (Passlick et al., 2019)

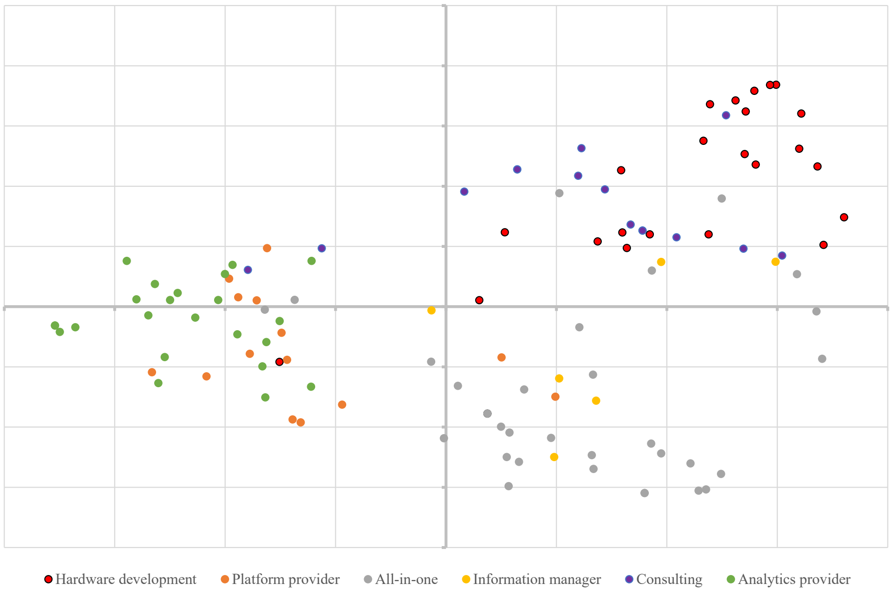

Figure 19: Visualization of the clustering using an autoencoder method

3.5 Discussions of results, implications and limitations

The previously described results show different approaches in the field of predictive maintenance for industrial machines. Spare parts management is essential for industrial companies to ensure productivity, but it is also important for capacity and costs. The presented model helps to calculate the tradeoff between possible breakdown and spare part provisioning costs. This model is accompanied by a service concept that permits a service provider to offer spare parts to its customer. The customer has the advantage of being able to adjust the number of spare parts in different periods and does not have to purchase a fixed number of spare parts. Customers are increasingly interested in having the guaranteed availability of their machines ensured, as has already been established for years in the IT sector for IT systems. The question is whether a machine builder or component supplier can offer such an availability-oriented business model. If they can, they could assume the role of the previously mentioned service provider and ensure that the right number of spare parts is either available at the customer site or promptly delivered. Otherwise, a completely external service provider will offer such a spare part provisioning service. To provide spare parts in a short time, detailed knowledge about the machines and components is required. These data are very sensitive for companies, as it is possible that they would allow the drawing of conclusions about output, productivity and quality. In general, a service provider will have several customers from similar sectors with similar machines and requirements. A high trust in the service provider must be ensured if companies are to share their data with it, and thus high requirements regarding privacy, security, and legal aspects need to be met. One input of the model is possible breakdown costs, which can be difficult for companies to precisely calculate. Machines are often used interchangeably in production, and so a breakdown will cause side effects. Different companies calculate their breakdown costs with different metrics, so it is difficult to compare them. This also applies to maintenance costs because it is difficult to calculate exact maintenance costs for complex machines (Faccio et al., 2014), and thus it is challenging for a service provider to calculate its fees, especially when companies are willing to pay for spare parts available in short time. Further research should be performed to help service providers calculate their provision costs for spare parts. First, input factors need to be worked out. This could, for example, be the time in which spare parts should be available, and a determination of whether they need to be stored at the service provider's site or at the customer. It is important for service providers to position their warehouses based on customer production facilities. Optimization models exist for the positioning of locations based on a certain demand, for example, the optimization of car sharing stations in terms of location and size (e.g., Olivotti et al. (2014) and Sonneberg et al. (2015)) or other models, which can be applied to the optimal positioning of warehouses (e.g., Salema et al. (2007) and Perl and Daskin (1985)).

The second approach presents a DSS with an optimization model to support maintenance planning, again with the use of condition monitoring data. A tradeoff between grouping machines in the same period to save costs and maintaining machines at their individual, optimal point in time, is considered. Manufacturing companies often have high dependencies on their machines. Therefore, maintenance is necessary to keep the availability of these machines high, yet maintenance activities also result in unscheduled or scheduled downtimes of a machine. A OEE of a machine is often calculated to see losses in efficiency in a production machine for various reasons or due to downtime. Further research should be performed on how the production schedule can be included in the DSS. Production plans are not always evenly distributed; periods exist where lower production capabilities are required other. For scheduled maintenance and downtime according to the actual condition of machines, this should be considered. The presented DSS for maintenance planning only considers the production topology indirectly by assuming the breakdown costs for each machine. Further research should be conducted on how the interplay of machines in the production and logistics processes can be modeled and included. An industrial machine is, for example, embedded in a production line. A breakdown results not only as a concrete broken machine but also as a standstill for the whole production line. Different typologies of a production flow should thus be included in the model, as these would help to estimate the costs and importance of certain machines to the whole process.

Third, a hybrid-learning monitoring approach for industrial machines is also presented, focused on the combination of machine learning and domain experience. The presented approach consists of three modules: anomaly detector, classifier and monitor. The anomaly detector module was developed and evaluated with real-world data from an industrial automation and engineering company. The other two modules are currently only developed conceptually. Further research should apply the modules by enacting test cases with real-world data. The presented hybrid approach works best in a value network where each participant shares its knowledge. Often, such a network consists of machine builders, component suppliers and service providers in the industry. Each of the participants has detailed knowledge of their domain. Component suppliers have detailed knowledge on the components they provide for machines. Machine builders have projected and planned the interplay of different components and automation solutions for their machines. Machine operators know how the machine works in daily business, its typical failures, the applications used and its load. If each of these participants works together and shares knowledge for the classifier module, valuable insights can be gained that could not be achieved by any single participant alone. This cooperation has to match the previously mentioned requirements regarding privacy, security and level of trust between the partners. For all presented approaches, a responsive dashboard and user interface must be created to help people easily work with the approaches. Interfaces with other systems, such as Enterprise Resource Planning (ERP) or sensor data management systems, help to reduce manual effort and failure probability and ensure acceptance of the system. It is important to have a single role-based human-machine interface to provide access to required information. This should contain asset and installed base data for the machine in a plant as well as predictive maintenance data. Specialized personnel should have access not only to the results from models for predictive maintenance but also to the raw data to perform root-cause analysis and further improve prediction models.

Reliable sensor information is required to generate a realistic model of the actual condition and is the precondition of all presented approaches. When monitoring the actual condition of the machine, different reaction times are needed. On the one hand, anomalies are detected that have a gradual impact, such as increased abrasion. This can be observed over a certain time, and maintenance actions can be planned. On the other hand, anomalies are detected in the short term, which has a much higher impact on machine breakdown. Here, it is typically only a few minutes or hours from the detection of an anomaly until a machine breakdown. In this case, the machine must be stopped to prevent expensive breakdown costs, the defective component can be changed and the machine can be saved from further damages. In addition to these two phenomena, errors also occur that cause an immediate machine stop or are not predictable.

To successfully implement predictive maintenance solutions, a reliable and scalable infrastructure is needed. A well-considered architecture based on cloud, edge and fog computing as well as machine hardware must be established. In a production facility, extensive data from machines could typically be collected. Two different approaches can be chosen or even combined. First, nearly all data could be collected to perform analyses, even if at the moment, it is unclear which data could be relevant. Second, the collected data can be classified as relevant for certain purposes. It must be kept in mind that devices (e.g., Programmable Logic Controller (PLC)) at the machine level often do not have enough processing power to perform large machine learning models. One approach to standardize transmission of data is Time-Sensitive Networking (TSN). The fourth paper presented addresses a taxonomy for predictive maintenance business models. The research shows that many companies recognize predictive maintenance as a promising business model. However, it is challenging to classify companies because various definitions of predictive maintenance exist. Often, predictive and preventive maintenance are not distinguished. The business models of companies are changing, especially through digital transformation. This study shows the actual situation of the 113 analyzed companies. However, archetypes are generally applicable and can be used for further classification and reclassification of the predictive maintenance business models. Predictive maintenance also has a strong relationship with quality management. Therefore, in an IWI discussion paper titled "Einflüsse der Digitalisierung auf das Qualitätsmanagement und die Notwendigkeit einer integrierten Betrachtungsweise anhand eines Referenzmodells" (Jürgens et al., 2019) presents a reference model for quality management driven by digital transformation. This paper is not further presented within this dissertation because it is not in the main focus. A promising further research would be to create a maturity model for predictive maintenance. This would help practitioners to localize themselves and to see which actions need to be taken going a step further. For different applications in the industry, different approaches for predictive maintenance are suitable. A reference architecture for predictive maintenance methods and models related to individual machines, component types and applications could further help practitioners. This reference architecture can have different focus areas. For example it could focus on data to give hints about which data are suitable for different applications and how it can be gathered. This can also result in standardized methods for the commonly used OPC Unified Architecture (OPC UA) framework.

3.6 Conclusion

The findings and discussions as well as recommendations in this chapter contribute to the field of predictive maintenance for industrial machines.

First, an optimization model for determining the optimal number of spare parts is presented. This model confronts the challenges of keeping spare parts in stock versus potential breakdown costs. This optimization model is combined with a new service concept to leverage the potential of having the service provider keep a stock of spare parts for different internal or external customers, which results in a smaller spare part stock and lower capital lockup. To achieve this, it will be necessary to have sensor data and to know the health status of components and machines. It is important to find not only the right number of spare parts but also the right point in time to perform maintenance activities. To support this need, a DSS is developed to group maintenance activities for several machines based on their actual condition. This helps to reduce downtimes and to calculate the overall costs for the maintenance of machinery in a plant. Similar to the first approach, the DSS is based on sensor values that determine the actual condition of a machine. The sensor values help to provide valuable insights into the actual condition and to perform predictive maintenance activities. Based on knowing the detailed condition of a machine, a third approach is presented: a hybrid-learning machine monitoring approach. This approach detects anomalies with the help of machine learning models and helps domain experts encounter faults before they occur. The hybrid approach is chosen because industrial components are present in very heterogeneous machines. By combining machine learning algorithms to detect a fault and a domain expert to perform a root-cause analysis, valuable knowledge can be leveraged. Especially when beginning to detect anomalies and using a predictive maintenance model, a hybrid model helps to train and further improve the prediction models step by step. The hybrid model is built on three main parts: an anomaly detector, a classifier, and a monitor. A real-world data set from an industrial engineering company is used for the development and training of the model. Predictive maintenance also offers potential for new business models as well as the extension of existing business models for predictive maintenance, as has been recognized by many companies. To structure the broad field of predictive maintenance business models, a taxonomy is therefore developed. Herein, the dimensions and characteristics of predictive maintenance business models are developed, and a cluster analysis is performed. Taxonomy development is performed according to a taxonomy development procedure from Nickerson et al. (2013). A total of 113 companies that offer predictive maintenance products or services are used to develop the taxonomy and are assigned to one of six archetypes of predictive maintenance business models. These archetypes help practitioners classify their current business model and think about either enhancing the model or building a new one.

4 Digital twins and installed base management in the industrial context

„Digital Twin is a hot new 'emerging terminology space', but this is a real thing, and modeling is at the heart of it."
Sky Matthews, CTO and Fellow, IBM Watson IoT

4.1 Motivation

The previous chapter described approaches and architectures for implementing predictive maintenance in the context of industrial machines. To support predictive maintenance, detailed information about the installed base in plants is required. Asset management as well as installed base management helps decisionmakers gain insights into their production plants. Asset management aims to support the life cycle of physical assets (S. Lin et al., 2006). Schröder and Sagadin (2013) see installed base management as a promising approach to asset management, whereas installed base maintenance focuses more on individual components and their interplay in machines and the environment (Dreyer et al., 2017; Olivotti, Dreyer, Lebek, et al., 2018). A shift in emphasis is recognized in the manufacturing industries, in that firms are not only selling physical products but also offering them along with (digital) services as PSS (Schrödl, 2013; Oliva and Kallenberg, 2003; Neff et al., 2013). Offering services to customers brings new sales opportunities and higher customer loyalty (Oliva and Kallenberg, 2003; Cohen, 2012; Barrett et al., 2015). Possible services for industrial machines are, for example, the management of spare parts delivery, predictive maintenance, and management and process consulting.

There is high demand regarding availability and productivity of industrial machines (Haider, 2011; Mert et al., 2016). To meet this requirement, detailed knowledge of the equipment is necessary. When offering services, to guarantee high availability, productivity sensor data and other condition monitoring data need to be processed (S. Lin et al., 2006; Fellmann et al., 2011). In addition, information that is gained during the life cycle (e.g., construction data, service data, maintenance data) of a machine or component is required. Condition monitoring data should be combined with the installed base data to obtain a comprehensive view. The academic literature has rarely addressed this topic to date. In manufacturing companies, different data sources are used, for example, ERP systems, Manufacturing Execution System (MES), Customer Relationship Management (CRM) systems and many more. These data sources are combined to obtain a comprehensive overview of assets, but obtaining such overview can be challenging, especially when considering whole value networks of component suppliers, machine builders and machine operators. The data need to be combined as digital representations in so-called digital twins. Digital twins are virtual representations of a physical asset, process or service (Kuhn, 2017). The product life cycle of a component or machine is often also represented in digital twins.

The paper “Towards a Smart Services Enabling Information Architecture for Installed Base Management in Manufacturing” (Dreyer et al., 2017) presents an information architecture for installed base management that aims to enable smart services for manufacturing industries. For smart services, detailed knowledge about the product is needed to offer data-driven services. Component suppliers in particular face the problem of having only limited knowledge about the individual component’s health status. Following the Action Design Research (ADR) approach, participants from practice and academia worked together in iterative cycles to develop the abovementioned information architecture for installed base management. An international engineering and manufacturing company was involved, and a test run was performed with real data.

Going a step further, the paper “Creating the foundation for digital twins in the manufacturing industry: an integrated installed base management system” (Olivotti, Dreyer, Lebek, et al., 2018) presents an installed base management system, building the basis for digital twins in the manufacturing industry. With the help of this system, component suppliers, machine builders and machine operators can gain valuable insights into their plant and machines. The ADR approach of the previous study is extended by two cycles and a detailed test run with the engineering company performed. For the test run, a demonstration machine is used. The generalization of results is achieved through the creation of design principals for the development and implementation of such an installed base management system.

4.2 Research design

An installed base management system for the manufacturing industry is developed in two consecutive papers. For this purpose ADR by Sein et al. (2011) is the underlying research methodology. ADR aims to close the gap between organizational relevance and methodical rigor in IS research (Lindgren et al., 2004; Iivari, 2007). ADR combines action research and design research in an integrated research approach. ADR tackles two main challenges. First, organizational relevance is required. The research approach supports problem solving in an organizational setting by fostering interaction between researchers and practitioners. Second, contributing to academic rigor is also required. ADR aims to develop generalized design principles from the formalized learning of organizational intervention. (Dreyer et al., 2017; Olivotti, Dreyer, Lebek, et al., 2018)

The applied ADR approach applied to the development of an installed base management system is shown in Figure 20. This approach includes the findings of both mentioned papers. The starting point of the research was the requirement from an international engineering and manufacturing company to develop an installed base management system.

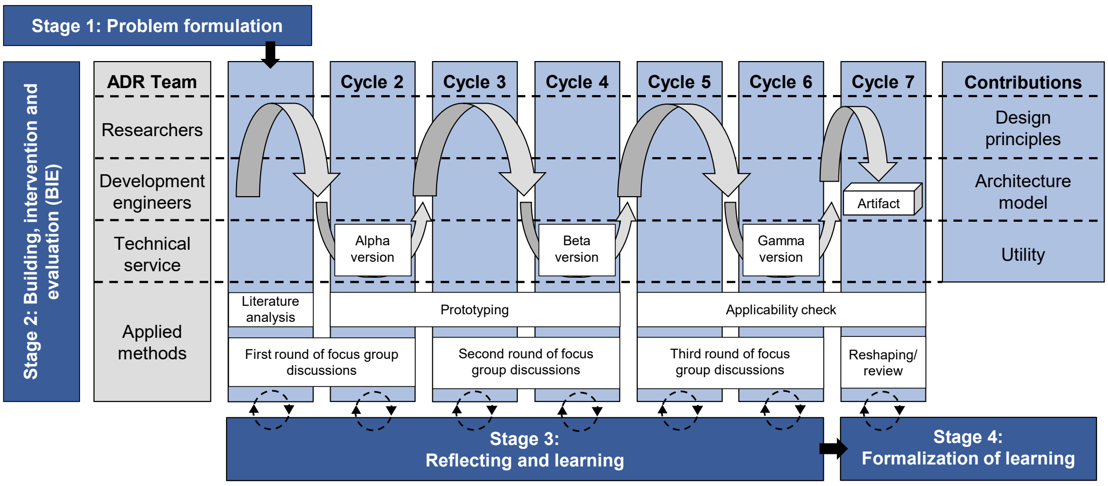

Figure 20: Research design based on the ADR approach from Sein et al. (2011)

This system should be able to organize and analyze installed base data of the company as well as from customers. This system set the basis for offering individual services in the context of installed base management for machine builders and machine operators. Stage 1 of the ADR approach addresses the mentioned problem formulation. The specific problem must be formulated as a broader class of problems. The ADR team formed in this study consists of researchers, practitioners and potential end users of the developed installed base management system. In detail, the team comprised researchers from a German university, practitioners from the firm IT department, innovation department, and product service account management department and end users from the customer service department of the target company. The broad range of different departments and competencies facilitated the problem formulation. The Building, Intervention and Evaluation (BIE) stage (Stage 2) consists of seven iterative cycles. Within the first cycle of the BIE stage, a prototype ("Alpha version") was developed. The requirements identified in the problem formulating state set the baseline, which built upon an analysis of the academic literature and a series of focus group discussions. For evaluation purposes, the developed alpha version was shown to end users and practitioners from the ADR team in cycle two during focus group discussions. To ensure transparency, the focus group discussion was documented and then evaluated by the researchers. The feedback gained in cycle two helped to further improve and extend the prototype ("beta version") in the third cycle. In cycle four, the improved prototype was again presented and discussed within the focus group. A particular focus was on relevance for the organizational setting to ensure that an extensive applicability check was started in cycle five. A test case for predictive maintenance was also defined. This test case was based on real data from the target company, which was used in a test run. Different data sources and types of data, including high-frequency sensor data, were used. The test run used the developed "Gamma version". To further support the test run, a demonstration machine was built and for it. This "Gamma version" was again discussed with practitioners and end users in cycle six. An incremental reshaping was performed in cycle seven, until the final version was reached. Simultaneously with the BIE stage, the reflection and learning stage was processed to evaluate each prototype version. This specific solution was generalized in the formalization of the learning stage to address a broader class of problems. Three main contributions were achieved in the ADR process. First, general design principles for the development and usage of installed base management systems were developed for researchers and academia. Second, the specific installed base management system helped the involved organization tackle their formulated problem, but the architecture aims for general applicability to manufacturing companies. Third, for the end users, the utility of the installed base management system helped them to perform their business tasks. (Olivotti, Dreyer, Lebek, et al., 2018) Figure 21 shows the research questions of the two papers. Both paper build together the mentioned seven cycle ADR process. The papers aim in answerring the following research questions RQ1: What are general design principles of an information architecture for installed base management that enables smart services? and RQ2: How can an integrated installed base management system be designed and implemented in the manufacturing industry?.

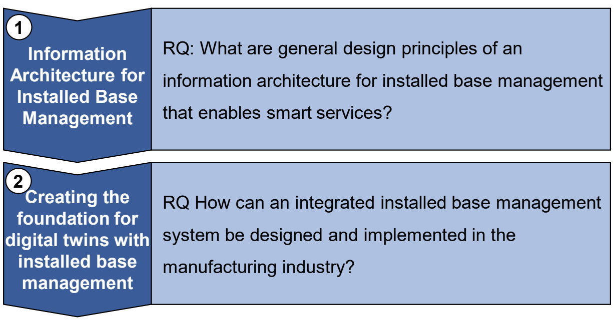

Figure 21: Research design overview - Digital twins and installed base management

4.3 Findings

The following described findings are based on the papers “Towards a Smart Services Enabling Information Architecture for Installed Base Management in Manufacturing” (Dreyer et al., 2017) and “Creating the foundation for digital twins in the manufacturing industry: an integrated installed base management system” (Olivotti, Dreyer, Lebek, et al., 2018). These findings are achieved through the applied ADR approach. In the first step, the problem of the involved manufacturing company is formulated. This manufacturing company has headquarters in Germany but operates in 60 countries worldwide; they focus on offering automation products and solutions.

During several focus group discussions with the target company and a German automotive manufacturer, the need for storage and usage of installed base management data arose. From the customer perspective, detailed information about the installed base in different plants is required. Furthermore, data for individual machines and included components and their individual conditions need to be monitored. The target company plans to offer services to machine owners to ensure maximum availability and production capacities. A portfolio of services based on installed base management was developed. Herein, predictive maintenance is chosen as a suitable example of an application of an installed base management service.

In summary, the following key requests for a predictive maintenance service were formulated:

- Installation errors are reduced or even avoided.
- Error causes and effects are identified immediately and reliably.
- Maintenance efforts are reduced.
- Maintenance schedules are optimally planned based on data.
- There is learning from experience, and knowledge is stored.
- Knowledge is provided in an understandable format at the right time and in the right place.

The six key questions contribute to the high availability of industrial machines. Therefore, an exemplary PSS was created. The involved target company is a component supplier and has detailed knowledge about their own products. Building a digital twin and localizing these components in industrial machines helps the firm to obtain a more comprehensive picture of the actual situation on the shop floor. The identification of each individual component (based on serial numbers) must be enabled. This results in a structured view of machines and their individual components. Based on this machine structure, individual product information and manuals should be available and further related to the task of the individual machine or component. For a machine operator, feedback on the health status as occurring anomalies or errors should be visualized in an integrated visualization cockpit. If immediate troubleshooting is required, the machine operator should be guided by step-by-step with instructions to solve the problem. If the machine operator cannot solve the problem, the maintenance staff would then need to advise. A knowledge base with occurring anomalies and errors as well as corrective action performed should be established for case-based reasoning and would also support the improvement of artificial intelligence and machine learning algorithms. With the knowledge gained, machine schedules can be adjusted, and machines would no longer need to be maintained according to fixed schedules but could be serviced based on the individual condition. An integrated installed base management system is required to store, structure, standardize and analyze installed base data. (Olivotti, Dreyer, Lebek, et al., 2018)

In different focus group discussions, general requirements for an integrated installed base management system were discussed. The participants stated that installed base data need to be aggregated from different data sources. Redundant data storage should be avoided. To create a digital twin with existing data, sensor data and additional manually recorded data are combined. A hierarchical structure is suitable for structuring machines and their components. According to S. Lin et al. (2006), data quality has been mentioned as a success factor for asset management and, consequently, for installed base management. To support the international interoperability of manufacturing companies, common data formats should be used. This results also in multilingual usage. An integrated installed base management system helps to avoid standalone systems and solutions. Existing databases can be connected and enriched with additional data; it would be necessary to analyze and visualize structured as well as unstructured data such as comments or user feedback. Analyses of individual components or analyses across various machines or production plants can help participants gain valuable insights. The developed integrated installed base management system is shown in Figure 22. (Olivotti, Dreyer, Lebek, et al., 2018)

The architecture is based on three main layers. The first layer is storage and processing; herein, different data types and data storage and processing systems are noted. Each company can store its data in different systems, and therefore, no connection between the mentioned data and systems is made in the architecture.

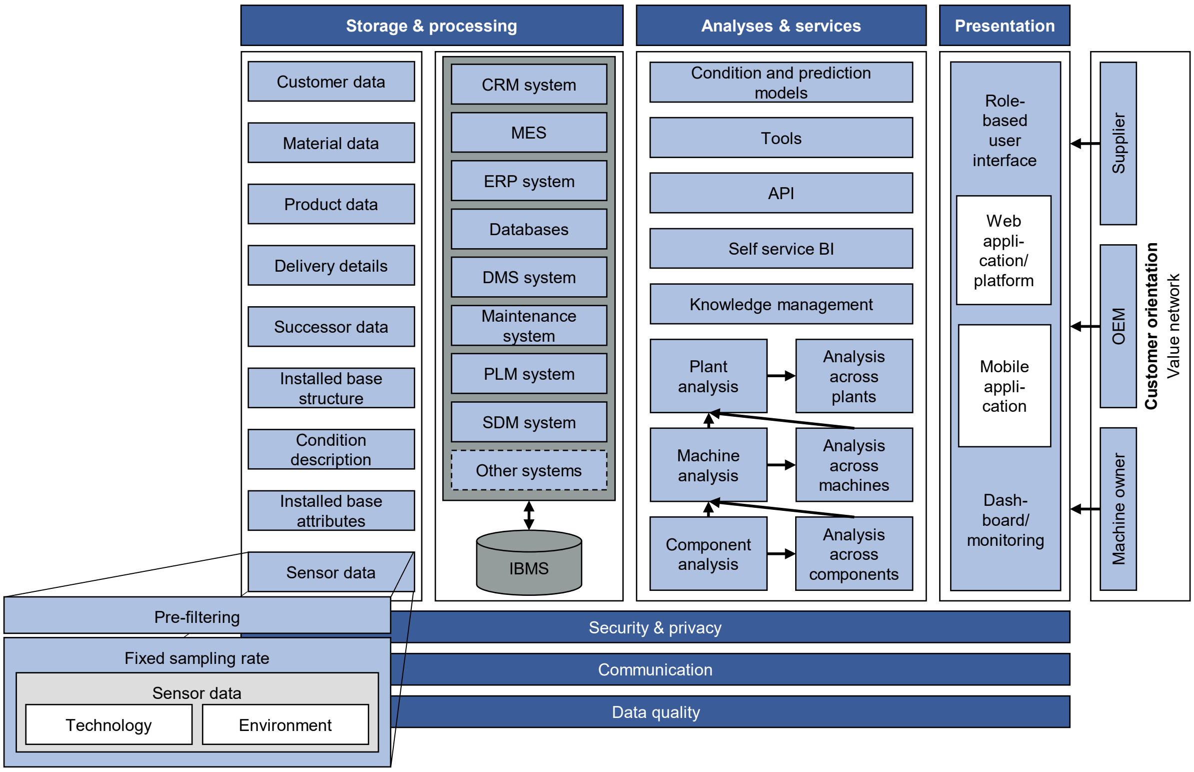

Figure 22: Integrated installed base management system

A special focus is on sensor data due to its importance for predictive maintenance services. All data saved in the different systems are aggregated and related to an installed base management system database. Because manufacturing companies operate worldwide and with different customers, the previously mentioned data can be stored by different participants in a value network. Typically, component suppliers or machine builders provide the main part of the data from their ERP, CRM and Product Lifecycle Management (PLM) systems. The machine operators complete it with data from the operations of the machines and localization in the production plant. Often, ERP, MES and Sensor-Data-Management (SDM) systems are used. The second layer of the architecture concentrates on analyses and services. To offer manufacturing services, the data from the first layer must be processed. Therefore, different analysis methods and tools can be used. Data related to components, machines and plants are compared. When offering predictive maintenance services, sensor data are particularly important. Further analyzing correlations across components, machines and plants can identify faults or savings potential. A knowledge management system helps to preserve knowledge gained through analyses or experienced employees. As mentioned in Chapter 3, combining domain knowledge and machine learning is seen as a valuable approach (Olivotti, Passlick, Axjonow, et al., 2018). The third layer addresses the presentation and the user interface. Different forms of presentation, such as mobile and web applications, are addressed herein; further, dashboards can be used to gain required information on KPIs, plants and machines. A role-based user interface helps different users focus on information that is relevant to them, though this is accompanied by permissions and security concerns. Three general functions are important for all layers. Data quality must be considered across all layers of the integrated installed base system. The same applies for communication, security and privacy. Security needs to be established on different levels, ranging from device level to the enterprise levels. It is essential that participants in the value network only have access to data that they are allowed to access. The value network is also an important element of the presented architecture. To ensure relevance for practice a comprehensive applicability check is performed (Rosemann M, 2008). This corresponds to the fifth to the seventh cycle of the applied ADR approach. The developed integrated installed base management system was set up in a test field. Based on this system, a test run within the target company was performed.(Olivotti, Dreyer, Lebek, et al., 2018)

The predictive maintenance test case evolved from a series of focus group discussions, and the results showed that the following functions should be supported and evaluated in the test case:

- Representation of machine topology
- Provision of individual documentation
- Provision of actual and past maintenance information
- Creation of maintenance schedules
- Condition-based maintenance
- Processing of sensor data
- Initiation of service requests
- Alarm signals and notifications
- Spare parts management and -ordering
- Enabling of remote Virtual Private Network (VPN) connections
- Visualization and dashboards/Key Performance Indicator (KPI)

To realize the test case, a physical demonstration machine was constructed to test the previously mentioned functions. The involved target company is an automation specialist

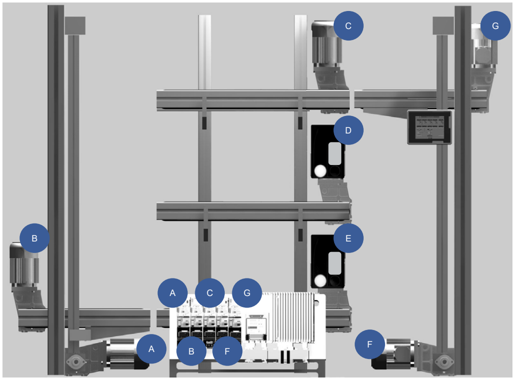

Figure 23: Schematic drawing of the demonstration machine

and component supplier, and automated goods transportation was the underlying application of the demonstration machine. A schematic representation is presented in Figure 23.

In total, seven machine axes permitted the material flow of goods. The machine axes were equipped with a geared motor and inverter each. The letters A to G in Figure 23 refer to the machine axes and their corresponding components. A central PLC controlled the movement of the different axes and their interplay.

Figure 24 shows an overview of the machine components and communications. The PLC aggregates sensor data from the demonstration machine and transfers it to an industrial PC. To gain more insight into the bearing, a special sensor was installed in the motor A.

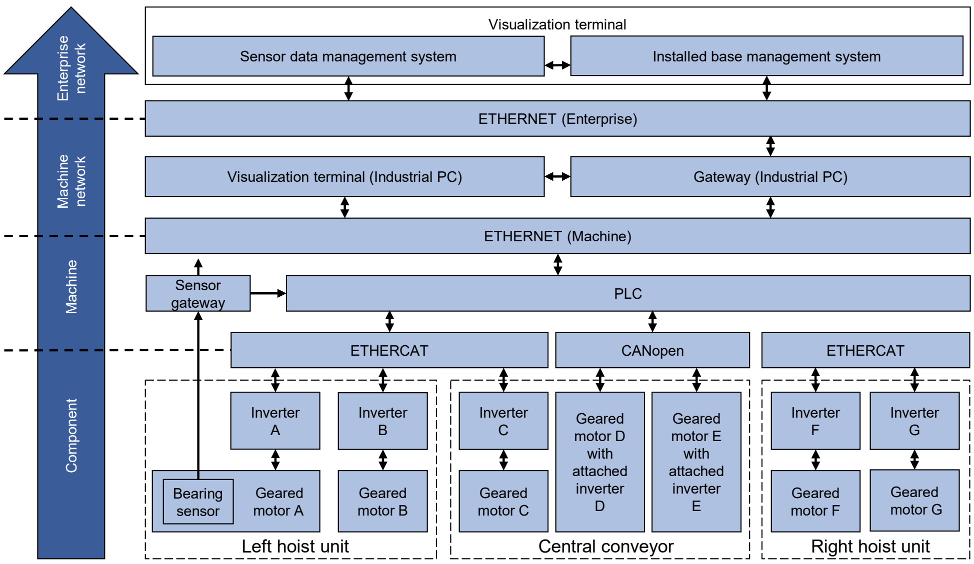

Figure 24: Schematic model of the demonstration machine

The data from this bearing sensor were transferred via a sensor gateway to the industrial

PC. From the industrial PC, the data were further processed into an SDM system. To support the machine operator, a visualization terminal was installed to show and monitor important parameters. In addition to sensor data, the machine topology is necessary for installed base management. To demonstrate the data model applied in the test case, a class diagram based on Unified Modeling Language (UML) was formulated. The class diagram applied to the test case is shown in Figure 25. A detailed description of the machine architecture and the class diagram can be found in the paper "Combining Machine Learning and Domain Experience: A Hybrid-Learning Monitor Approach for Industrial Machines" (Olivotti, Passlick, Axjonow, et al., 2018).

The test case shows that the required functions could be successfully implemented. The developed integrated installed base management system aims toward generic usability, so it should be applicable to various services and not only predictive maintenance services. The system further contributes to the creation of digital twins for offering individualized services. Following the ADR approach, the learning should be formalized. For this purpose, general design principles were formulated as contributions to academic knowledge. Table 9 shows the formulated design principles. Additionally, standards and best practices were added for each design principle. For installed base management, transparency is important. An easy-to-understand structure of machines and components must be provided, and identification using the individual serial number of individual components enables digital twins.

By identifying an individual component such as a specific manual or a spare part, it can be provided. Transparency accompanies data quality as a basis for reliable analysis. Standardization helps to reduce customization and foster collaboration in value networks. Defined data formats should be used for data exchange, and data should be standardized to allow processing by automated tools, which requires machine-readable data. An agreement on standards facilitates cooperation between companies but is a challenging process. International agreement is required because many companies operate worldwide and in worldwide value networks, and, for example, international data formats and multi-language support are necessary. Special focus is required for security and privacy: sensitive company information or sensor data are used for installed base management and so unauthorized access must be prohibited to prevent data loss and machine down times. This can be achieved by VPN or certified-based authentication. A suitable infrastructure and technical realization is required for installed base management, which includes collection and processing large amounts of sensor data from industrial devices. Common used protocols are Message Queuing Telemetry Transport (MQTT) and OPC UA. In addition, interfaces to enterprise systems need to be managed.

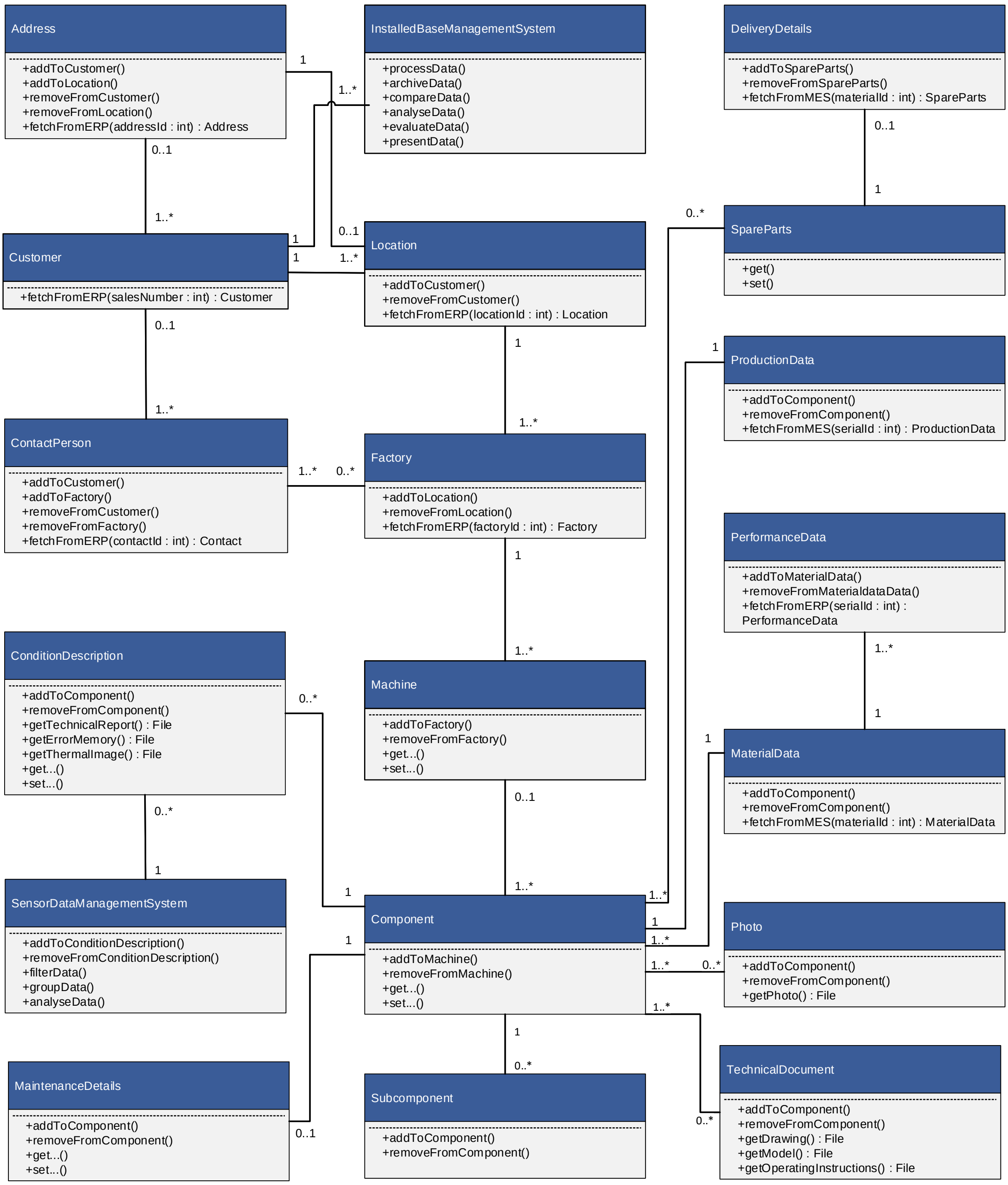

Figure 25: Class diagram applied to the test case

Table 9: Set of design principles

Design principle	Description	Examples	Standards/ best practices
Transparency - Consistent vocabulary - Clear allocation of components - Clear identification of products	A clear hierarchical data structure and naming that is consistent and generally comprehensible are necessary. An unequivocal identification of the products contributes to a clear structure and the creation of a digital twin.	Uniformly-named components and serial numbers for unequivocal identification of components	International Standard Serial Number (ISSN)
Standardization - Uniform data format - Machine readability of data	Analyses are simplified due to a uniform data format. This contributes to a general understandability of the data for different target groups and ensures readability by machines.	Uniform sensor data format, enabling exchangeability between companies	eCl@ss, AutomationML, Extensible Markup Language (XML)
Internationality - International data format - Transferability to other languages	Organizations in the manufacturing industry often operate worldwide which is why it is important that the data has an internationally understandable format. The transferability to other languages contributes to this.	Multiple-language data maintenance, uniform date format	ISO (e.g. date/time ISO 8601)
Security & Privacy - Adaptable structure depth - Adaptable access rights	The data is used by different participants and users. Therefore, a role-based authentication with different read and write permissions is required.	Selective transaction authorization	One-time passwords (OTP), Certified-based Authentication (CBA)
Infrastructure & Technical realization - Suitable interfaces - (Real-time) Data processing	An infrastructure capable of collecting and processing large amounts of data is a necessary precondition for offering installed base management services.	Sensor data collection, production data import, data and information forwarding	MQTT, OPC Unified Architecture (OPC UA)
Scalability - management of different data volumes - management of different numbers of sources	Factories can be expanded, or new plants can form part of the installed base. The installed base management must support changes in quantity of data and sources.	Higher frequencies of sensor data, implementation of new machines	
Analysis - Across components, machines, plants - Unstructured data	Collected and processed data can be analyzed, independent of whether they are structured or not.	Comparing the state of different machines, analyzing unstructured comments in text boxes	Apache Hadoop, NoSQL
Service orientation - Integration into corporate strategy - Integration into existing business models	Individualized services must be offered in accordance with the corporate strategy of a company. Existing business models must be considered to expand the range of services sensibly.	Predictive maintenance services of machine manufacturers as an extension to product sales	ITIL V3
Visualization - Adaptable dashboard - Data/information visualization in real-time	Individualized dashboards show sensor data and further information. All information the digital twin contains are displayable and visualized.	User-dependent view, dashboards, KPIs, push notifications, intuitive and responsive interface	HTML5, CSS3
Value network - Across partners of the network	Installed base management is realized in value networks. All partners must be considered to realize a digital twin.	Component suppliers, machine builders, machine users	Value network analysis (VNA)

Systems must be scalable because technical infrastructure and data quantity can change in quickly. All the collected data can be used for analytical purposes to gain insights. Not only can the components and machines be analyzed but also similar components could be compared. Different techniques and tools are used for structured and unstructured data, and the visualization of data and information can help decision makers take action. Therefore, individualized dashboards are required, and all information for a digital twin must be accessible from one place. Combining physical products with individualized services is a promising approach. This service orientation must be integrated into corporate strategies and existing business models. A greater number of value network members participating in the creation of an installed base management system means that better services can be offered based on digital twins. (Olivotti, Dreyer, Lebek, et al., 2018)

4.4 Discussions of results, implications and limitations

The previously shown findings are related to installed base management and digital twins. Installed base management can therefore be seen as an enabler of digital twins. In general, digital twins are not only product related but can be seen much further. Information about each digital representation of a product can be combined to obtain an overview of a whole production plant. Tao and Zhang (2017) call this the “digital twin shopfloor”. The presented installed base management system helps to initiate installed base management in the manufacturing industry. However, the term installed base management must be specified in more detail. In the literature, the terminology is rarely discussed, and so a definition is provided in this dissertation and the underlying publications. Additionally, the presented architecture suggests which aspects can be summarized under the term installed base management.

The presented research includes an applicability check with a comprehensive test case for an innovative manufacturing company in the automation sector. This was a good starting point, but further case studies with several companies need to be performed. Because the field of manufacturing is very broad, different companies have different requirements. It would also be helpful for whole value networks to be considered and end-to-end processes analyzed. Typically, components suppliers, machine builders and machine operators are considered But service providers are also seen in such value networks or the mentioned partners assume the function of a service provider. The test case in the study focused on predictive maintenance, which is a promising approach in the industry. Addressing predictive maintenance service provides valuable insights for the installed base management system, although other services such as big data analysis, spare part management, warehouse services and worker guidance should be considered in further research in more detail.

Digital twins are often discussed in close relation to CPS in the production context (Uhlemann et al., 2017; Negri et al., 2017). To realize such CPS, cloud systems and architectures are often used. Alam and El Saddik (2017) present a digital twin reference architecture for Cloud-Based Cyber-Physical Systems. Tao and Zhang (2017) identify "interconnection and interaction in the physical shopfloor" as one of the key technologies for implementing digital twins on the shopfloor. To obtain precise information, machines and material flow systems need to be connected and information aggregated in the installed base management system. This means that interfaces between systems need to be built carefully and considered in detail. This brings high potential but results in more complexity while monitoring these interfaces carefully. An increasing number of systems are connected to each other, and data are transferred between them, in practice, these are, for example, ERP, MES, PLM. Each company must define for itself which systems are most suitable for its needs. Based on these, a data model can be created for installed base management. An example is therefore shown in the UML diagram in the findings section.

Additionally, high-frequency sensor data are mentioned in the presented findings and architecture. For sensor data, a suitable infrastructure must be provided to obtain data in the required time.

To help practitioners to implement digital twins in their production facilities or products, reference architectures are one possible approach. A reference architecture for installed base management is presented in the previously described findings. Alam and El Saddik (2017) present an architecture reference model for cloud-based CPS in relation to digital twins. Other authors also see the combination of digital twins and CPS as a promising approach (e.g., Negri et al. (2017), Uhlemann et al. (2017), and Tao and Zhang (2017)). The first approach to a maturity model for data-driven manufacturing is presented by C. Weber et al. (2017). Further research on maturity models for digital twins in the manufacturing industry should be performed to allow practitioners to see which maturity level they have reached and to obtain concrete recommendations on what actions need to be performed to reach the next step.

4.5 Conclusions

The approaches in this chapter contribute to the topics of installed base management and digital twins in the manufacturing industry based on two scientific publications. The first publication focuses on an architecture for installed base management enabling smart services. Following ADR, the architecture is worked out with researchers, practitioners and end users of an industrial engineering company. The ADR methodology is further used to extend the study and improve the architecture. This leads to an important extension in the context of sensor data. Not only is the architecture itself extended but also the design principles for practitioners. In addition, an extensive applicability check is performed focused on predictive maintenance within the engineering company. A real-world machine is used to gain sensor data from its components, which are mapped to a digital twin. The research also shows that installed base management has not yet been addressed in the literature. Digital twins attract high research interest. Digital twins are based on installed base management; therefore, the developed architecture contributes to the field of digital twins and helps create such digital twins.

5 Product service systems and business models in the industrial context

„If you're competitor-focused, you have to wait until there is a competitor doing something. Being customer-focused allows you to be more pioneering.“

Jeff Bezos, Founder, Chairman, and CEO of Amazon Inc.

5.1 Motivation

A shift in emphasis is being seen in the manufacturing industry. The offering of physical products is less often the sole focus, and it is becoming common to combine physical products with services in so-called PSS. PSS are accompanied by new business models in the manufacturing and capital goods industry. This chapter is based on three papers. The paper "Focusing the customer through smart services: a literature review" (Dreyer, Olivotti, Lebek, et al., 2019) describes the customer-centric offering of smart services. This systematic literature review helps to cluster the broad field of smart services. A definition for smart services is given, and a visual heat map is created to show hot and cold research areas and provide suggestions for further research.

The paper "Modeling Framework for Integrated, Model-based Development of Product-Service Systems" (Apostolov et al., 2018) presents an approach to modeling PSS in the manufacturing industry. Based on the Systems Modeling Language (SysML) the integrated, model-based framework helps to address the development of PSS. A use case from a German automation company demonstrates the applicability in practice.

PSS also leads to new business models. Therefore, insights from chapters 3 and 4 are required to to offer a model based on the availability of industrial machines. In the paper "Realizing availability-oriented business models in the capital goods industry" (Olivotti, Dreyer, Patrick Kölsch, et al., 2018), realization based on a use case is shown.

5.2 Research design

This chapter is based on four papers that all contribute to the field of PSS, smart services and new business models in the manufacturing industry. The resulting research design is shown in Figure 28. The paper "Modeling Framework for Integrated, Model-based Development of Product-Service Systems" (Apostolov et al., 2018) uses a Model-Based Systems Engineering (MBSE) approach to support the design process of PSS. This paper answers the following RQ: How can the integrated, model-based development of PSS be supported by a modelling framework? The result is a concrete modeling framework. The approach is based on the MBSE approach, and SysML is used as the overall modeling language; in particular, SysML's predefined diagrams and modeling specifications can be used. To facilitate usage and specification by practitioners and organizations, a single model is chosen. It is important that the model covers the physical parts as well as the service component of the whole system. The system model is a computer-interpretable description of the PSS and a record of decisions made during development (Apostolov et al., 2018). The tools in the modeling repository support the creation of such models. The aim of the model is to also support different stakeholders and value networks; therefore, an object-oriented approach was chosen to facilitate the exchange of knowledge and common understanding. Because it is widely used in MBSE and is easy to understand, SysML is used. The presented integrated model is based on the Kaiserslautern System Concretization Model (KSCM) based on Eigner et al. (2017). To show applicability in practice an applicability check in accordance with Rosemann M (2008) is performed. This is done with the help of a German automation and engineering company.

In the next step, smart services are analyzed in the paper "Focusing the customer through smart services: a literature review" (Dreyer, Olivotti, Lebek, et al., 2019) in detail because they are gaining increasing importance in the manufacturing sector. Therefore, a detailed literature review based on Webster and Watson (2002) is performed. The paper answers research question RQ1: How does academic literature conceptually approach smart services along the smart service lifecycle? and RQ2: Which research gaps and related further research opportunities can be derived from prior research on smart services?. Webster and Watson (2002) state that it is essential to review the relevant literature to create a basis for future research. The aim of this paper is thus to provide a comprehensive overview of the relevant literature through a systematic literature search. Such an overview is important because it creates a logical structure around the most important concepts and aspects and allows research gaps to be identified (Webster and Watson, 2002). According to Webster and

Watson (2002), the first step is identifying the literature relevant to the topic. In the second step, the articles are structured to obtain an overview of the literature identified in the first step. Webster and Watson (2002) recommend using a concept matrix to provide the structure. In a concept matrix, all articles identified as relevant are listed. Each row refers to an article identified in the first step. Each column refers to the specific concept addressed in the article, which allows one to check which concepts are relevant for each article. This matrix gives a good overview of which concepts are already widely used and allows research gaps to be seen: it is important to identify not only relevant papers but also research gaps, new theories and concepts (Webster and Watson, 2002).

The search process for the presented research is shown in Figure 26 and described here. In the first step, a search of eight databases was performed using the search terms "smart

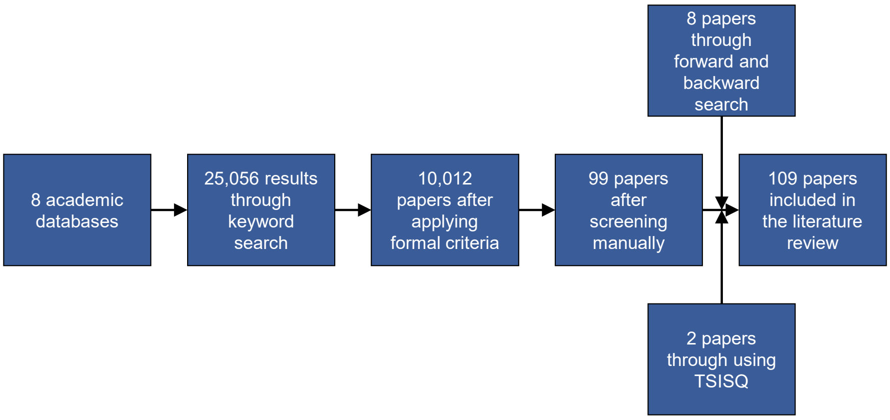

Figure 26: Literature search process

service, digital service, electronic service". The plural forms, abbreviations and synonyms of the terms were also used. The databases searched were chosen because they contain the most relevant papers in the Information Systems Research (ISR) field. Where possible, a search of the abstract or title was performed; otherwise, a full-text search was performed. The search resulted in 25,057 total hits. To reduce this number, criteria were next applied; for example, non-peer-reviewed and nonscientific papers were excluded, as were papers written in languages other than English. After applying the criteria, 10,012 papers remained. These papers were screened manually to check whether they were related to the ISR field and whether they focused on smart services. Those papers found using the keywords 'digital service' and 'electronic service' were checked to see if they aligned with our definition of smart services. This step required high effort and resulted in a reduction to 99 relevant papers. According to Webster and Watson (2002), forward and backward search should be applied. For the backward search, the citations of each article were checked for further relevant papers. The forward search was carried out in Google Scholar to find articles that cited the already-identified articles. In addition, the literature search tool Tool for Semantic Indexing and Similarity Queries (TSISQ) developed by Koukal et al. (2014) was used. This tool uses latent semantic indexing to find semantically similar text in several databases. After this step, the final database contained 109 papers representing the result the literature search.

Building on the extensive smart service literature, the relationship between knowledge-edge management and smart services is analyzed. The paper "Knowledge Management Systems' Design Principles for Smart Services" (Dreyer, Olivotti, and Breitner, 2019) aims to answer the RQ: How can customer-centric knowledge management systems for smart services be designed? The research design is shown in Figure 27.

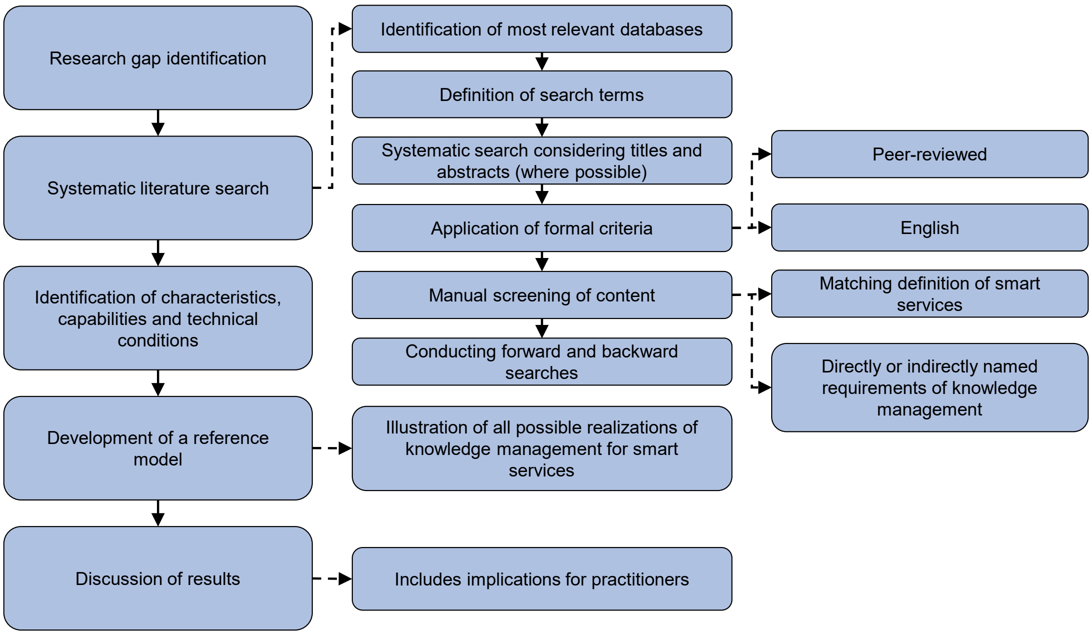

Figure 27: Research design

The above-described literature search for smart services was extended and actualized, and the papers were checked to see if they addressed knowledge management. Often, they did not name knowledge management explicitly but did identify implicit requirements. The identified aspects from the literature were then assigned to one of the following categories: characteristics, capabilities, or technical functions. These categories were developed during the literature analysis process, and the papers could be assigned to exactly one category. On that basis, a Knowledge Management System for Smart Services (KMSSS) was developed. A reference model was then developed following the approach of Becker and Delfmann (2007) that helps to show the diversity of tailored KMSSS. An applicability check is performed and shows a tailored KMSSS for a predictive maintenance use case within the previously mentioned automation and engineering company. Afterwards, the results are discussed and implications for practitioners given. Last, the paper

"Realizing availability-oriented business models in the capital goods industry" (Olivotti, Dreyer, Patrick Kölsch, et al., 2018) show evaluation results of an availability-oriented business models. Avalaibility-oriented business models are interesting for indsutrial companies since machine breakdowns are very expensice. Therefore the RQ: How can availability-oriented business models realized and applied in the capital goods industry? is answered within the paper. Based on a research approach according to P. Kölsch et al. (2017) a predictive maintenance use case from a German engineering and automation company is applied.

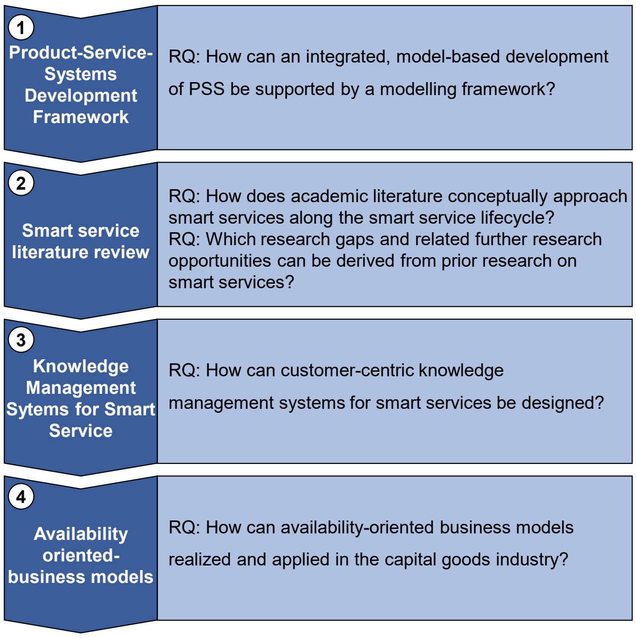

Figure 28: Research design overview

5.3 Findings

5.3.1 Modeling framework

The paper "Modeling Framework for Integrated, Model-based Development of Product-Service Systems" (Apostolov et al., 2018) presents a framework for the design of PSS. In the manufacturing industry, a shift in emphasis towards PSS can be seen. Companies offer new services along with their physical products, and PSS enable new business models. Higher complexity is observed during the development phase of such PSS (Apostolov et al., 2018). PSS often rely on value networks, and the service component adds complexity in the form of IT usage, data management and data analytics. To support the development of PSS PSS and ensure a structured procedure, a model-based, integrated development approach is presented within the mentioned paper. The general structure of the integrated PSS and ensure a structured procedure. The general structure of the integrated PSS modeling framework is shown in Figure 29. The model is built upon three

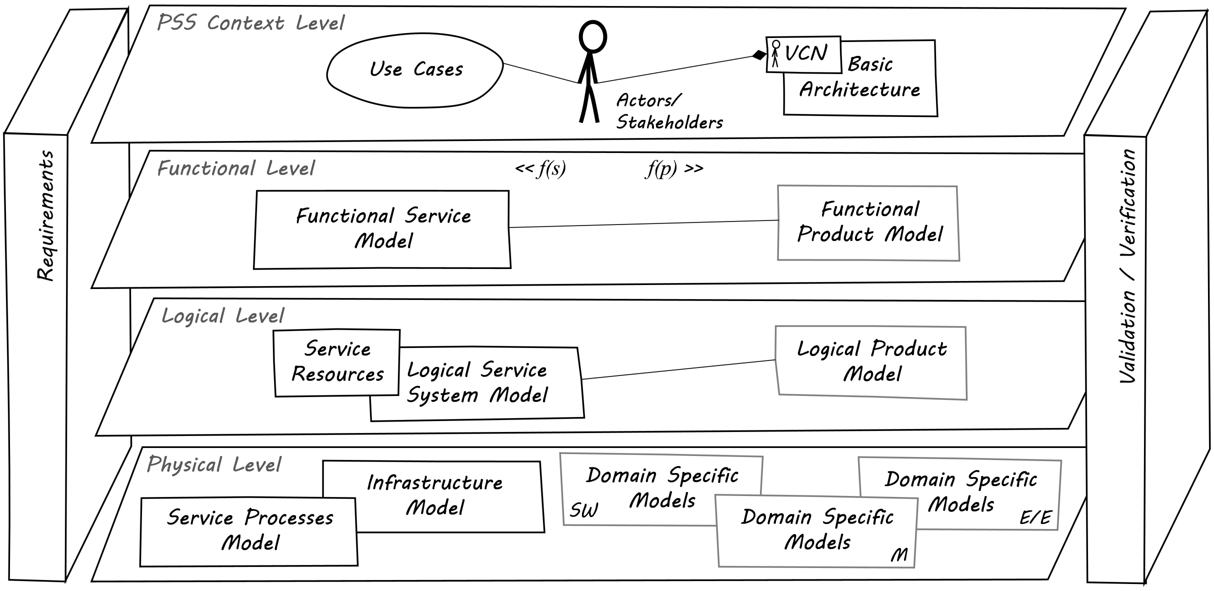

Figure 29: General structure of the integrated PSS modeling framework

spaces. In the middle of the model, the solution space consists of four abstraction levels: the physical level, logical level, functional level and PSS context level. On the left side is the requirement space, which defines the requirements over all four abstraction levels of the solution space. On the right side of the model is the validation and verification space, containing test cases based on the solution space. At the beginning of PSS development, the requirements of the business and for the model need to be specified and documented; this occurs in the requirement space of the model. It is important to involve the different stakeholders at the beginning of the requirement stage to gain their contributions. The overall goal of the required PSS should be formulated based on these requirements. This can be done with concrete use cases that describe the PSS with a focus on customer orientation. In this step, if relevant, the transformation from a physical system to a PSS should be described. It is also important to specify the context in which the PSS PSS is being developed and will afterwards be used. To maintain the scope, a clear system border is defined. This results in a basic architecture and the value-creation network required for the corresponding PSS. Within the functional level, the previously described high-level elements are further detailed with concrete functions and functional requirements are addressed. The defined use cases are supplemented by activities. Alternative solutions for functions are discussed with the stakeholders and decisions made for the realization of the PSS. Chosen and rejected functions are documented. In this step, activities are allocated to the product level, to the service level or to both. The logical level further specifies the previously described functions: concrete elements are chosen for the realization of the required activities are chosen and assigned to logical operations. In the next step, the flow of information and physical elements between different elements is modeled. This is not only relevant for the PSS; the flow outside the defined system border and the interface to other systems need to be modeled. In the physical layer, maximum concretization is achieved: the resources required for operational procedures are specified, including IT systems and software as well as material and personnel. This set also serves as the foundation to start implementing the concrete PSS. To support implementation, the validation and verification space provides detailed information about the fulfillment criteria of the functions and test cases for implementation. (Apostolov et al., 2018)

To show applicability, an extensive use case within an automation and engineering company is performed. This company provides important automation parts for machine builders, for example, including gearboxes, motors, inverters and controllers in its product portfolio. The following use case focuses on an availability-oriented business model. The goal is to ensure the availability of industrial production systems with the help of smart maintenance policies and models for the involved components in a machine. Smart services such as condition monitoring and predictive maintenance are included in the use case. A focus on the components alone is insufficient; the interplay between the industrial machines is also important. Therefore, asset management and installed base management services are required (Dreyer et al., 2017; Olivotti, Dreyer, Lebek, et al., 2018) (see also Chapter 4) to build digital twins of the machines and the processes. During the production process, sensor data are used to obtain details about the condition of components with the help of lifetime models. In combination with other asset and installed base data, detailed insights can be generated for a machine. These sensor data are also necessary in case of a failure, as they make it possible to track the history of component replacement and to have all the necessary information on hand. To realize the use case and create sufficient data, a real-world demonstration machine was built and used. In the following, some views and diagrams used during the creation of the PSS for the company are described. For further details, it is refered to the paper "Modeling Framework for Integrated, Model-based Development of Product-Service Systems" (Apostolov et al., 2018). It must be kept in mind that each diagram describes only parts of the whole model. For this reason, not all properties and dependencies are shown in the diagrams. Figure 30 shows a requirements diagram. Herein, the formulated stakeholder requirements from the requirement space are visualized and associated with each other. At this point, only the requirements and the context are established. The goal of the PSS with service units can be found in Figure 31, which also includes the participants of the involved value-creation network. The service units are further broken down into a SysML block definition diagram (see Figure 32), which shows the basic structure of the PSS.

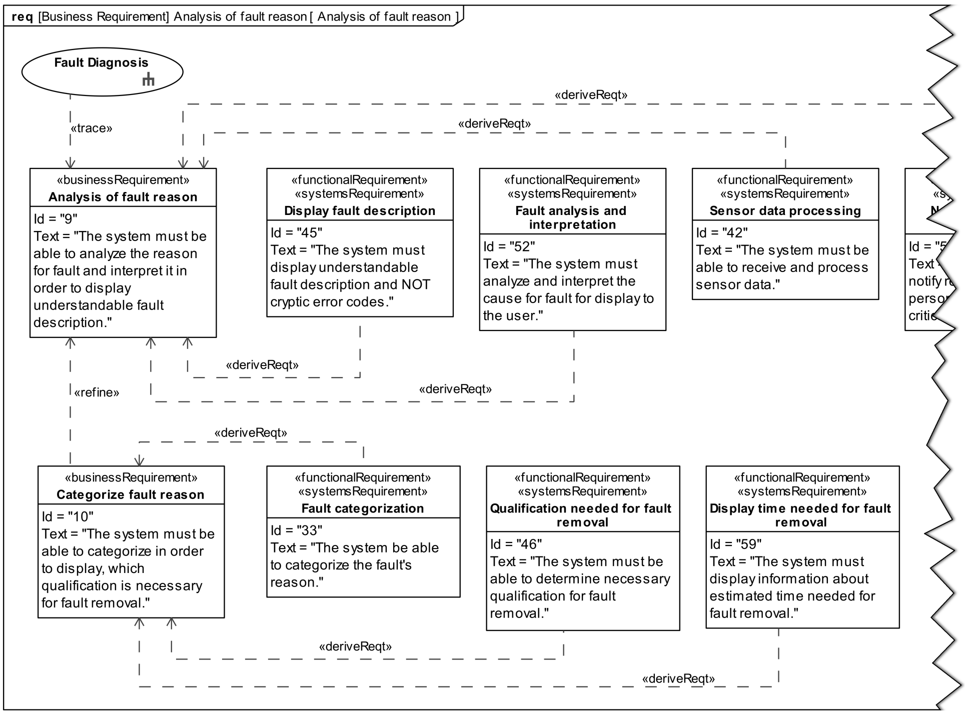

Figure 30: Requirements diagram of the business requirement “Analysis of fault reason” displaying associated system requirements and use case (excerpt)

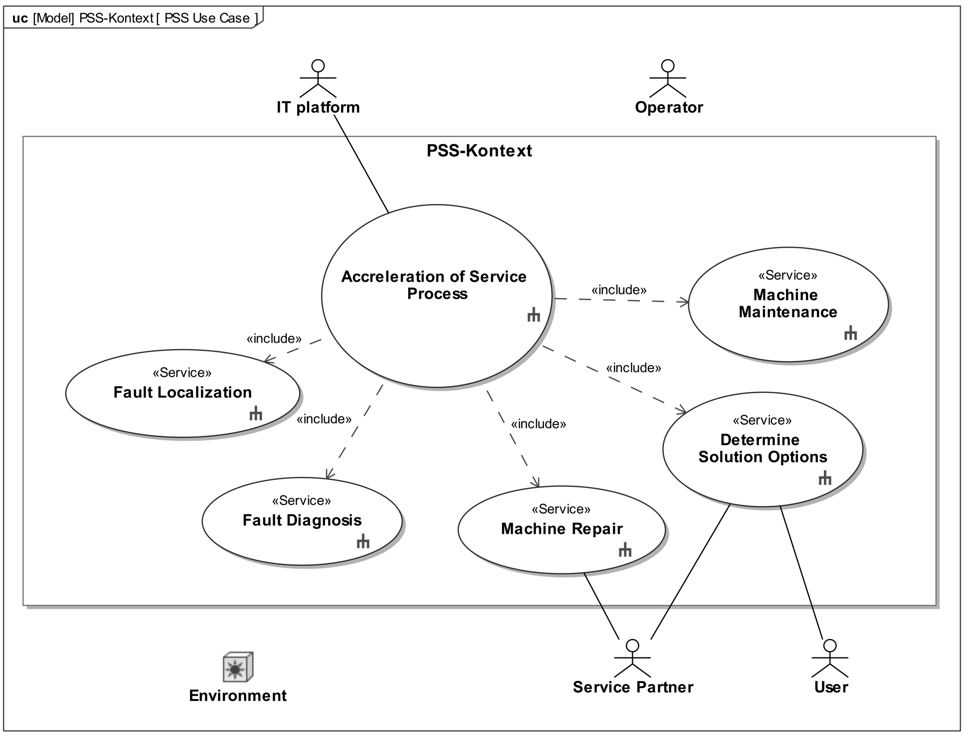

Figure 31: Definition of the PSS goal and service units

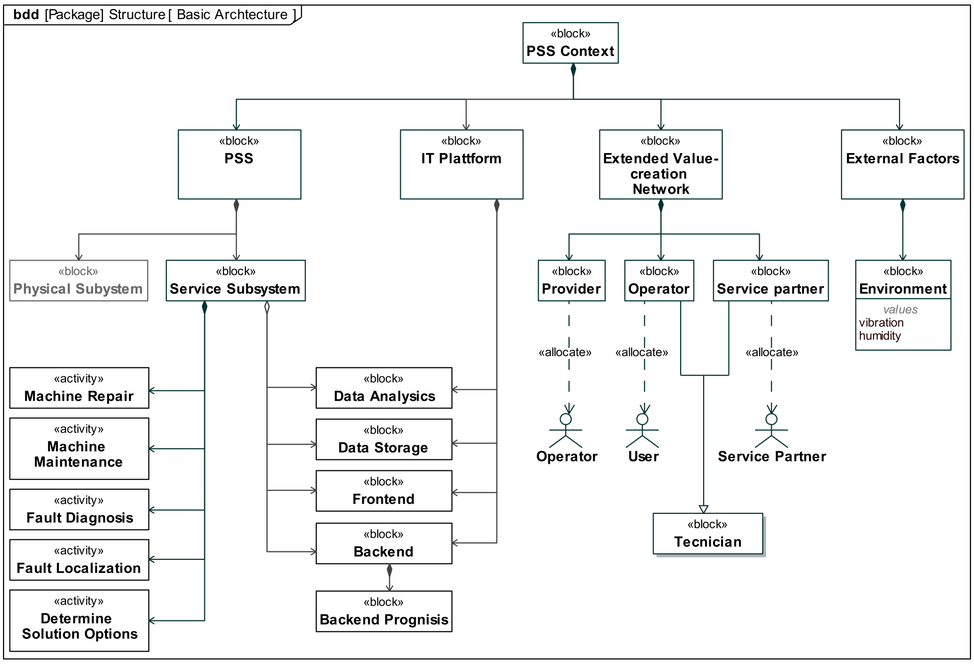

Figure 32: Basic structure of the PSS in its context

The diagram divides the PSS into a physical and a service subsystem, but the physical subsystem is not specified in detail and only the interfaces are considered. In the presented PSS, the IT platform plays a central role, and it is linked to the relevant blocks of the service subsystem. In addition to the mentioned point, the extended value-creation network and external factors are considered. The presented service units must also be specified in detail. Figure 33 provides an example of an activity specification, specifically the fault localization activity that is needed to identify a fault in a machine based on collected sensor data. The diagram shows the logical order of the activities in the con-

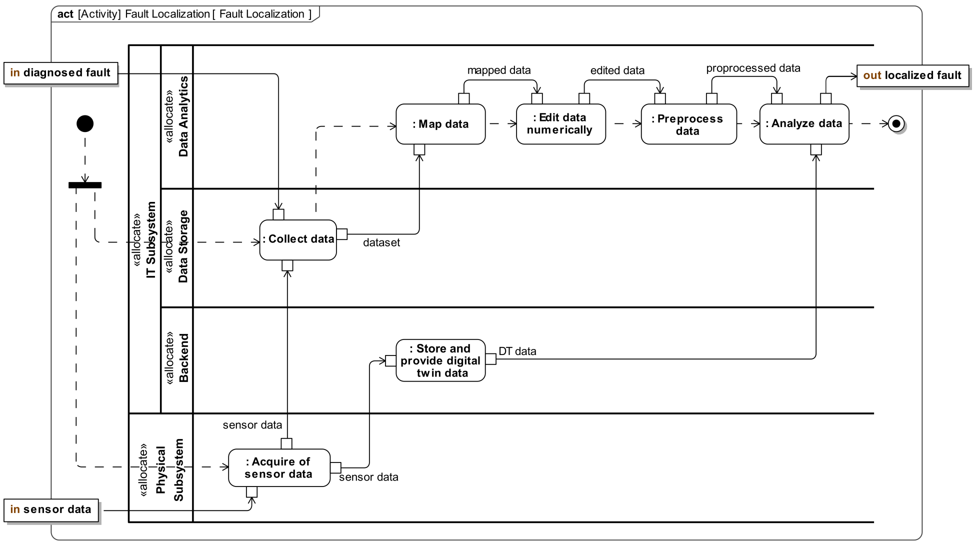

Figure 33: Activity specification of the service unit “Fault localization”

sidered service unit, and the object flows are also modeled. The IT components and the

IT infrastructure are important aspects of the PSS. These aspects were only indirectly addressed in the previous diagrams, and to focus on them in more detail, an internal block diagram is created. The internal structure of the IT infrastructure of the service subsystem is shown in Figure 34. In this diagram, the information objects and the links

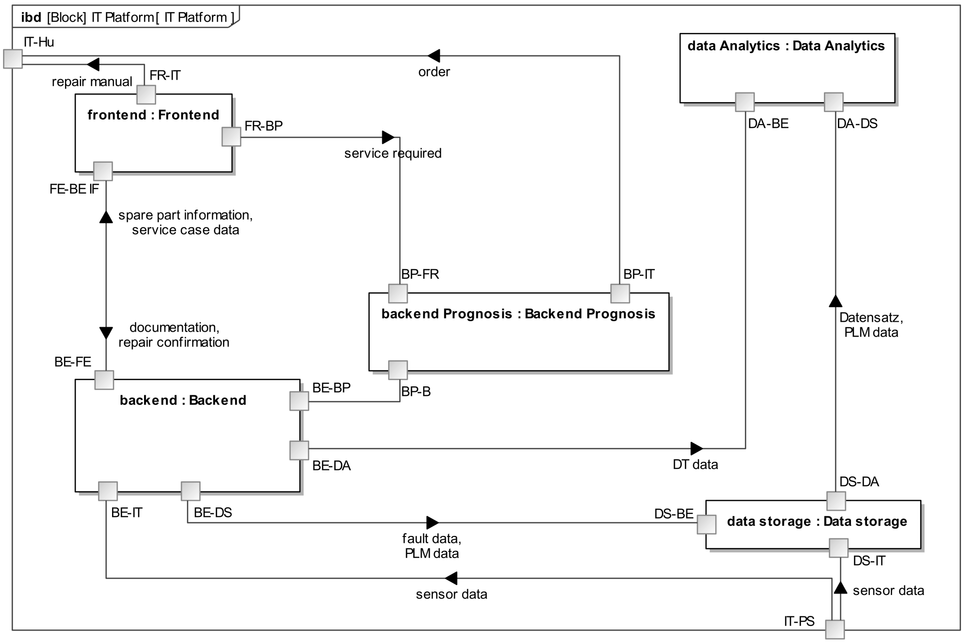

Figure 34: Internal structure of the supporting IT infrastructure of the service subsystem

between them are shown, with product data being included as information objects. The data objects are also linked to service steps or actions. These diagrams are only a smart extraction of the complete model: the different views created by the diagrams help to focus on certain parts of the model. The presented use case shows the applicability of the model in practice. For each diagram or part of the model, feedback is gathered from the different stakeholders to ensure that relations and elements were modeled correctly. The results also show that the development of the PSS is a complex process that captures much more than physical assets. Often, more partners in the value-creation network are involved in the development of a PSS, and the IT portion is greater.

5.3.2 Smart services

A shift in emphasis is being seen, as described earlier, from selling only physical products to offering product combined with services (PSS). Customer needs are changing continuously, and to fit the needs, smart services can help. Smart services are customer-centric services with high flexibility based on ICT. Growing interest in smart services can be seen in the literature as well as in practice in recent years, but a comprehensive literature review and the structured identification of research fields is missed. To address this issue, "Focusing the customer through smart services: a literature review" (Dreyer, Olivotti, Lebek, et al., 2019) presents a structured literature review based on Webster and Watson (2002). Herein, 109 relevant publications were identified and analyzed. These results are clustered according to a smart service life cycle and 13 main topics of interest. The research design and the literature search process were described previously, and the results from the literature analysis are described below.

Figure 35 shows the smart service lifecycle as applied to this research. Given continuous changes in customer needs, smart services must also change. Therefore, a lifecycle following the Information Technology Infrastructure Libary (ITIL) framework seems to be a suitable approach to classify smart services. The identified papers for smart services

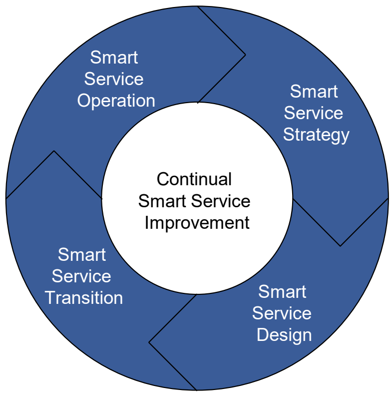

Figure 35: Smart service lifecycle following the ITIL framework

were assigned to one or more of the smart service lifecycle phases, which resulted in a better structuring of the papers and supported further analysis. A detailed overview of which publications are assigned to which phase can be found in the paper "Focusing the customer through smart services: a literature review" (Dreyer, Olivotti, Lebek, et al., 2019). After assigning each publication to the relevant lifecycle phase, key topics were identified, as shown in Table 10. The following section of this dissertation provides only a small extract from the broad analysis. The smart service strategy phase is represented by 25 papers. In this section, technologies are discussed from a strategic point of view (e.g., Ferretti and D'Angelo (2016) and Perera et al. (2013)). Paluch and Nancy V. Wünderlich (2016) describe six risk types when dealing with technology-based service innovations. Eight papers focus on data in the strategic phase and identify data as a key factor in the provisioning of smart services (Dreyer, Olivotti, Lebek, et al., 2019). A total of 59 papers are assigned to the smart service design phase, which represents the largest number of papers assigned to a phase of the smart service lifecycle. Different approaches to the design of a smart service and concrete examples from practice are found in these papers.

Table 10: Key topics in the literature and aspects focused on in the context of smart services

Topic	**Focus on**
(Big) Data	Data analysis Importance of data for smart services
Business models	General approaches for business model deisgn Concrete business models
Customer involvement	Role of customer Customer requirements
Knowledge management	Technologies for information processing Means of showing or applying information
Machine learning	Approaches for specific functionalities General approaches for using machine learning for smart services
Pricing	Pricing strategies Analysis of different pricing models
Security/privacy	Role concepts and user management Security and privacy concerns
Service quality	Measuring the quality of smart services Aspects of smart service quality
Standardization	Of data and information Of technological aspects
Technology	Technological perspective on smart services Discussions of appropriate technology Presentation and evaluation of infrastructure
Trends	Future trends of smart services
Usage behavior	Measuring and analyzing usage behavior Perspectives for applying knowledge of usage behavior
User interface	Examples of user interfaces Theoretical contributions on how a user interface supports smart services

An important point mentioned is that standards are required. Kryvinska et al. (2008) see open standards as necessary for new services. Another topic mentioned in the literature is security and privacy (e.g., Keskin and Kennedy (2015), Cellary (2013), and Gretzel et al. (2015)). During the design phase, customer involvement must also be a focus. N. V. Wünderlich et al. (2013) describe value cocreation as a key aspect of smart services. For the smart service transition phase, a total of 40 publications are found. In this cycle, technologies and big data (analysis) are in focus (Dreyer, Olivotti, Lebek, et al., 2019). Services based on various technologies are seen as promising approaches (Paluch and Nancy V. Wünderlich, 2016). For big data and the usage of real-time data, the research shows different foci. On the one hand, studies in this area recognize high potential in the usage of such data and the fulfillment of customer needs (Tuán et al., 2012). On the other hand, challenges and potential risks are also identified (Nuaimi et al., 2015). The user interface plays a central role and is mentioned by several papers (e.g., Mukudu et al. (2016), Oh et al. (2010), and Pao et al. (2011)). The managed usage of knowledge is also mentioned. Chu and S.-W. Lin (2011) and Li et al. (2015) state that smart services are knowledge intensive, and therefore knowledge management is required. For the smart operation phase, only five papers are identified, showing that little attention has been given in the literature on the operation of smart services until now. The papers in this phase mainly focus on the usage of technologies and data for monitoring or failure detection (e.g., Lee et al. (2010), Hamdan et al. (2012), and Baldoni et al. (2010)). More papers are found addressing continual smart service improvement (19 in total). The most important aspect mentioned among this group is service quality, for example, by Kwak et al. (2015) and Yu (2004).

Each of the papers is assigned to at least one lifecycle phase and one topic. To identify the research gaps and give indications for further research, a heat map is created. The heat map shows the topic on one axis and the lifecycle phase on the other. The color in the heatmap goes from blue (few papers assigned) to red (many papers assigned). The heatmap can also be found in the mentioned paper (Dreyer, Olivotti, Lebek, et al., 2019). Based on the heatmap, five research areas are discussed in detail, and promising suggestions for further research are given.

5.3.3 Knowledge management

The paper "Knowledge Management Systems' Design Principles for Smart Services" (Dreyer, Olivotti, and Breitner, 2019) focus on the design of knowledge management systems for smart services. A detailed literature analysis helps to work out characteristics, capabilities and technical conditions for knowledge management for smart services. This aspects are used for the developed reference model. To show applicability a real-world example is presented.

In the following the characteristics of KMSSS are described. These characteristics are shown in Table 11. In the next step functional capabilities identified in the literature

Table 11: Identified characteristics of KMS

Characteristic	**General requirement**	**Smart service's requirement**
Usage across departments	✓	✓
Usage in value networks		✓
Input sources are diverse	✓	✓
Usage by both people and machines		✓
Dynamic	✓	✓
Transparent	✓	✓
Applied in different contexts		✓
Standardized knowledge	✓	✓

are shown in Table 12. They are classified if they are a general requirement or a smart service specific requirement. For detailed description of the characteristics and functional capabilities it is referred to the paper by Dreyer, Olivotti, and Breitner (2019). At last

Table 12: Identified functional capabilities of KMS

Functional capability	**General requirement**	**Smart service's requirement**
Integrability of many types of knowledge	✓	✓
Combining knowledge	✓	✓
Generating knowledge automatically		✓
Reaction in real-time		✓
Efficient storage	✓	✓
Efficient management	✓	✓
Avoiding redundant knowledge	✓	✓
Generalizing context information		✓
Meeting security and privacy concerns	✓	✓
Situation-sensitive output		✓
Standardizing knowledge	✓	✓
Reliability and robustness	✓	✓

technical conditions are identified. This technical conditions can be found in Table 13. Smart services are based on the usage of IT technologies. Therefore it is important to match the technical conditions for the offering of smart services.

Table 13: Identified technical conditions of KMS

Technical condition	General requirement	Smart service's requirement
Interfaces to other tools and IS		✓
User interface	✓	✓
Integrability in a middleware		✓
Role-based authentication		✓

As shown diverse types of smart services and also designs of KMSSS exists. To show the dimensions of the KMSSS design a cube reference model is proposed. The reference model is shown in Figure 36. The first dimension of the model described the input and output.

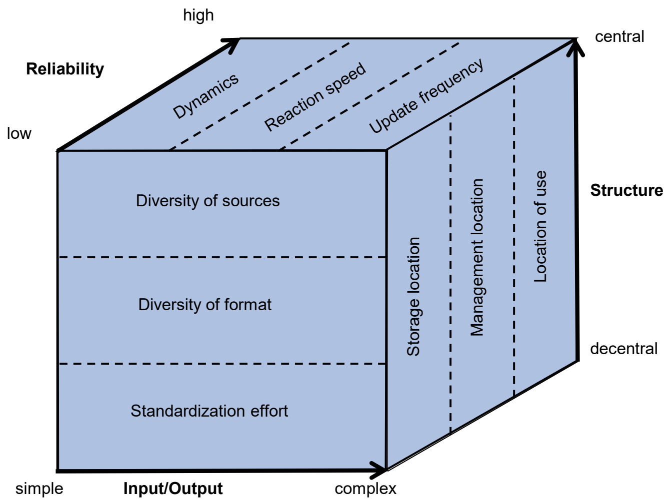

Figure 36: Knowledge management system for smart services reference model

Each knowledge management system could have different input sources (Delfanti et al., 2015). The complexity depends on the number of sources and of the type of sources. For example structured text can be handled with lower effort than voice or image recognition. Berná-Martínez et al. (2006) mention standardization along with knowledge for smart services. Depending on the KMSSS standardization can be easy or a very challenging tasks (Tianyong et al., 2006). Knowledge can also be generated during the operation phase of a smart knowledge and used to further improve the smart service or gain further value (Cellary, 2013). The same characteristics can also be assigned to the output of a smart service. The second dimension of the model is called structure. Storage location of knowledge is important to consider, especially in value networks (Ferretti and D'Angelo, 2016). Knowledge can be stores on a central repository or in several decentral places. Also a combination of both types is possible. For example sensible data is stored locally and not shared across all participants of a value network. The same applies to the usage of the knowledge. Central models can be provided on a server or decentral execution of models can be performed. In value networks often a central knowledge manager is responsible for the KMSSS. The third dimension of the model is called reliability. Smart services are often highly dynamic (Batubara, 2015) due to changing customer needs. In fact KMSSS need to be also flexible to support such an dynamic smart service. Therefore this is also addressed in the reference model. Smart services could be based on nearly real-time data and quick reactions are necessary (Holgado and Macchi, 2014). The KMSSS need to match this reaction speed requirements. Depending on the KMSSS the update interval of knowledge differs (Strüker and Kerschbaum, 2012). For each smart services the relevant dimensions of the cube model can be checked to find the most suitable design of a tailored KMSSS.

To show applicability of the developed reference model based on the previous identified characteristics, functional capabilities and technical conditions an applicability check according to Rosemann M (2008) is performed. An overview about the concrete example can be found in Figure 37. This real-world example considers a value network of a compo-

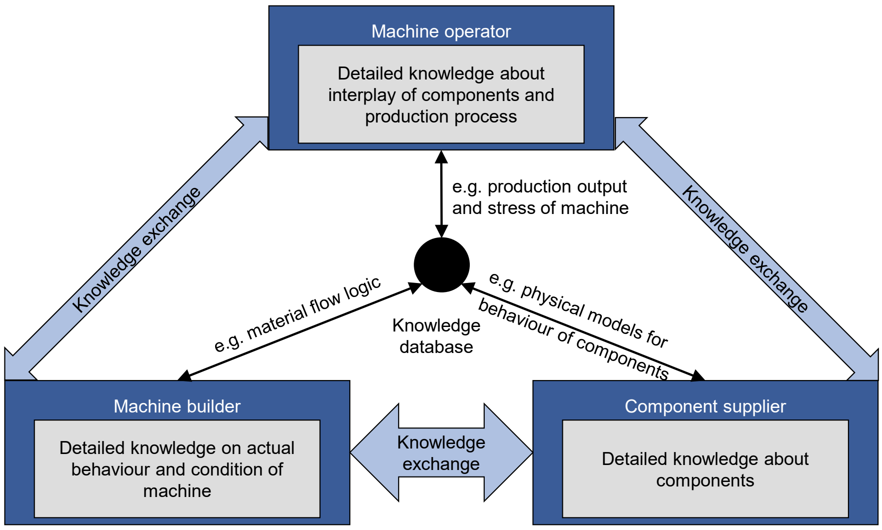

Figure 37: Exemplary knowledge flow in a value network for predictive maintenance activities

nent supplier, a machine builder and a machine operator. In Chapter 3 this value network is explained more in detail. Each of the value networks partners have detailed knowledge on either their components, machines or the operation of machines. To support a predictive maintenance use case and to reduce downtimes of machines the knowledge is shared. Within this KMSSS it is important that all partners benefit from sharing their knowledge. To predict failures or anomalies of machines detailed knowledge about the machine and components need to provided nearly in real-time. This requires a suitable infrastructure to deal with this high-frequent data stream and to perform analysis in time. Industrial machines are often protected because sensor data can draw conclusion on production output and efficiency. Therefore the KMSSS need to provide mechanism to enable sharing of knowledge only to intended partners of the value network and protected from competitors for example.

5.3.4 Availability-oriented business models

A shift in emphasis towards PSS can be recognized in the manufacturing industry, and the question is if machine builders or service providers can offer their customers guaranteed availability. The paper "Realizing availability-oriented business models in the capital goods industry" (Olivotti, Dreyer, Patrick Kölsch, et al., 2018) presents validation results of a concept for availability-oriented business models. Building on design thinking, a concept with five steps was developed and validated by means of an automation and engineering company. The results also show the applicability of the concept and provide suggestions for further research. Following an action research approach, the concept was developed with researchers from German universities and partners in the industrial sector. The concept is shown in Figure 38. TThe use case for validation is in the context of

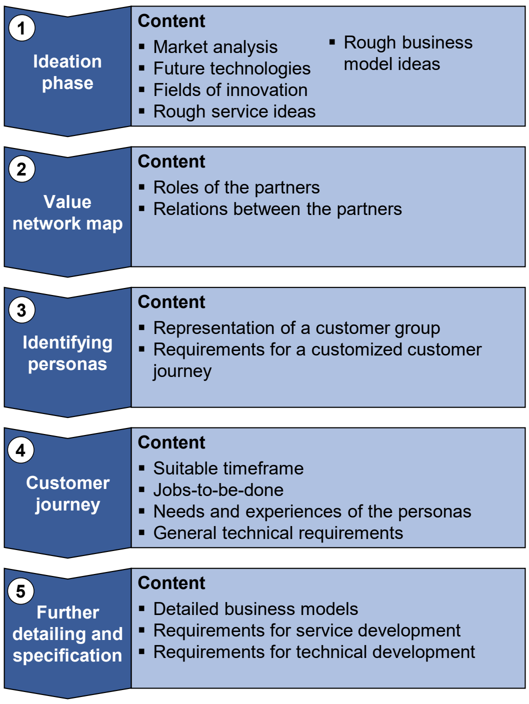

Figure 38: Concept for the development of availability-oriented business models for PSS (P. Kölsch et al., 2017)

predictive maintenance, and a real-world demonstration machine is used, detailed information about which can be found in Chapter 4. During the ideation phase, market and technology trends were analyzed. Through several focus group discussions, search fields were defined and clustered. For this search field, market analysis was performed, and the status quo was defined. Data analytics are especially indicated for the mentioned use case. In the next step, the value network map is developed (shown in Figure 39). In the

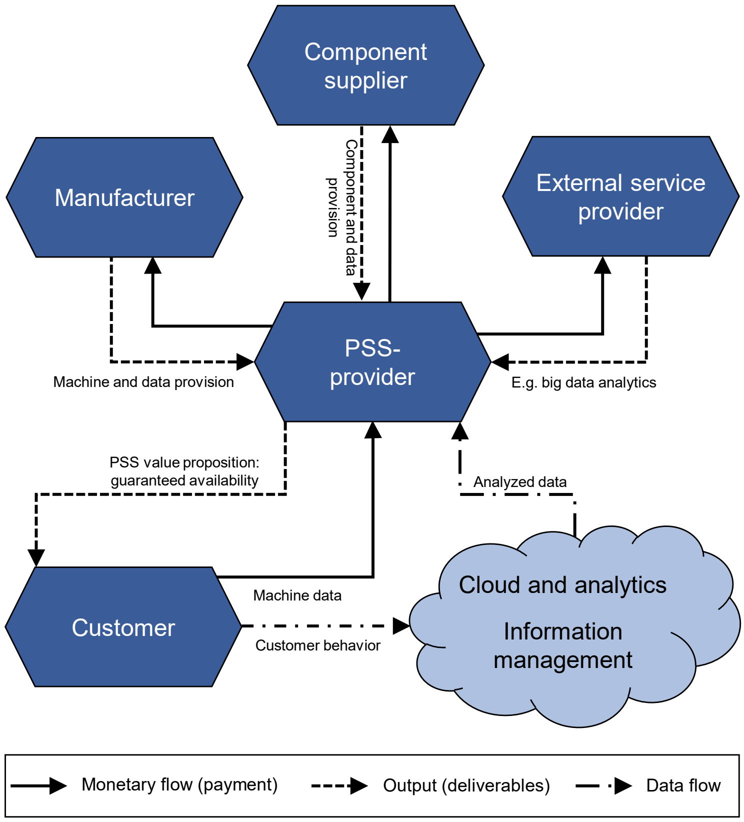

Figure 39: Value network map

middle of the value network, the PSS provider manages data flow as well as output and monetary flow. The component supplier delivers components to the manufacturer, and the manufacturer can use these components in various applications and scenarios that have different requirements. The customer is the machine operator and uses the machines for his production process. External service providers could also exist, for example, for data analytics services. It is important to note that the PSS provider could also be one of the partners of the value network; this is highly dependent on the value network and the partners whether a participant acts as the PSS provider. In the third step, relevant personas are identified, and four personas were concretized in detail. Machine operators want to use an industrial machine: they are interested in the high availability of their machines and want to have detailed knowledge about their condition, and so information regarding maintenance and operation should be easily accessible. In the case of an error, the machine operator should be notified and defined actions triggered. Second, service technicians and maintenance staff are interested in ensuring the availability of machines and reducing downtime as much as possible. They also need detailed knowledge of the machine and the specific maintenance guides. With the help of sensor data, they can localize faults and repair machines efficiently. Service technicians often execute the service on the shop floor, where the maintenance staff coordinates their work, and conduct deeper analysis and correlations. Following the model, in the next step, concrete scenarios are elaborated based on the customer journey. In the first scenario, an error occurs with a machine that results in a breakdown. The machine operator can resolve the error by following a detailed guide. The most likely cause of the error is shown to him, along with a possible solution to fix that error. The machine operator gives feedback to ensure that the model for calculating the probability of default for each root cause is improved. In the second scenario, the fault cannot be solved by the machine operator, and the system suggests that the operator call a service technician. The service technician has access to detailed insights about each machine, including past activities and life cycle information. In the last scenario, smart maintenance planning is addressed. It is important for a service provider to keep an eye on the machines, for which he has offered guaranteed availability. On that basis, he can plan maintenance activities based on the real condition and not in fixed intervals. The fifth step in the concept for the development of availability-oriented business models. is further detailing and specification. Here, the concrete functions of the predictive service are modeled and specified. The predictive maintenance service is described in total with concrete data and defined documentation. The presented industrial use case on predictive maintenance shows the applicability of the concept and what a concrete business model can look like.

5.4 Discussions of results, implications and limitations

In this chapter, the results of the four papers are presented. The first paper, called "Modeling Framework for Integrated, Model-based Development of Product-Service Systems" (Apostolov et al., 2018), provides insights into the development of a PSS. The framework aims for general applicability in various scenarios. Therefore, it provides a high-level framework, and companies must choose the level of detail at which they will model the PSS and which views are the most important. Tools for product life cycle management can help to support the design phase as well as the subsequent operation and maintenance of the PSS. Further research is needed on how such a modeling framework can be used in different companies with various requirements. Depending of the seize and the type of company (e.g. component supplier, machine builder, machine operator) different requirements for services are needed. Therefore, a multicase study is proposed. Additionally, the value network needs to be considered in more detail, along with how to design flexible system borders. Considering value networks helps to model flow of information, monetary value and who will offer which service more in detail. In the second paper "Focusing the customer through smart services: a literature review" (Dreyer, Olivotti, Lebek, et al., 2019), the smart service literature is analyzed in detail and suggestions given of research gaps. Smart services are a promising approach in relation to the IIOT. For companies, smart services are challenging because they must react to changing customer needs quickly. However, smart services make it possible to have continuous interaction with the customer and to obtain immediate feedback from the customer. Further research should be performed on what types of smart services look like that and potentially define several archetypes. This can be performed which a similar research methodology as in the paper “Predictive Maintenance as an Internet of Things enabled Business Model: Toward a Taxonomy” “Predictive Maintenance as an Internet of Things enabled Business Model: Toward a Taxonomy”. Smart services are data driven. Another interesting question would be what data models for smart services look like. These data models help to build up a suitable infrastructure and fulfill technical requirements like data seize and frequence. Third, the paper “Knowledge Management Systems’ Design Principles for Smart Services” (Dreyer, Olivotti, and Breitner, 2019) focuses on knowledge management in the context of smart services. Because data are essential to knowledge management, the data sources are very important. Depending on whether they are structured or unstructured or which type is used, different techniques and tools are required to process the data. For example, using a Structured Query Language (SQL) database differs from performing semantic text analysis. As suggested in Chapter 3, a hybrid approach can be appropriate. The hybrid approach combines the domain knowledge of experts with machine learning models or other methods and models. In the manufacturing industry, extensive domain knowledge is present, and prediction models are often difficult to develop. Smart services are changing continuously; therefore, the knowledge management system must also provide a certain flexibility. Further research should be performed on what an architecture for knowledge management would look like. In addition, a maturity model can help to show different stages of knowledge management for smart services. Finally, the validation results of availability-oriented business models are presented in the paper “Realizing availability-oriented business models in the capital goods industry” (Olivotti, Dreyer, Patrick Kölsch, et al., 2018). The predictive maintenance use case shows the application to one case. In the industrial sector, various value networks exist, and therefore, it is challenging to develop a model that fits them all. In each network, it must be determined who will act as the PSS provider. This can also result in discussions among partners, since traditional business models are established. If a component supplier starts interacting directly with the customer, the machine builder will fear losing revenue channels. In addition, further research should be performed on how availability-oriented business models can obtain benefits and how prices are calculated.

5.5 Conclusions

In this chapter, PSS and smart services are discussed in the context of the manufacturing industry. Additional new business models that are arising from the previously mentioned trends are discussed. Initially, the development of the PSS is supported through the means of a model-based, integrated framework. This framework helps practitioners to keep an eye on the whole PSS design lifecycle. The framework aims towards general applicability and the use of IT supported tools. Similar to PSS, the term smart services is also common. Smart services are customer-centered services using ICT and different types of data. A comprehensive literature review is performed to provide insights into the broad field of smart services. The systematic literature analysis derives research gaps and a definition of smart services. During the smart service literature analysis, knowledge management emerged as a promising aspect of smart services. Various knowledge management system designs exist for smart services. To structure the topic, a reference model is developed for KMSSS. Along with the reference model, guidelines for practitioners are proposed. PSS and smart services result in disruptive changes to existing business models or the introduction of new business models for companies. Industry claims guaranteeing the availability of their industrial machines are becoming common. Therefore, availability-oriented business models are required, and service providers must offer them. Within this dissertation, the validation results of such an availability-oriented business model for an automation and engineering company are shown.

6 Overall discussions, limitations and further research

This cumulative dissertation aims to contribute to the field of digital transformation in the manufacturing industry. Different scientific papers are discussed in three main chapters within this dissertation. A discussion of the results and limitations of the papers is given in each of the three main chapters. This chapter aims to perform an overall discussion of the research field and to show the relationships between the three chapters. overall Further limitations and suggestions for further research are also given here.

The first main chapter, Chapter 3, illustrates two models that optimize the number of spare parts and maintenance planning of industrial machines. Further, a hybrid-monitoring approach is presented, combining machine learning and the domain knowledge of experts,. Finally, a taxonomy for classifying predictive maintenance business models is shown and discussed. The second chapter, Chapter 4, addresses installed base management for industrial machines. This sets the foundation for the creation of digital twins in the manufacturing industry. An installed base management architecture is proposed along with design principles and recommendations for practitioners. In Chapter 5, a modeling framework is proposed for the design of PSS. An extensive literature analysis for smart services is presented as well as a reference model for knowledge management in relation to smart services. Finally, an application of availability-oriented business models for industrial goods is shown.

These presented approaches show the complexity of the topics and technologies that are in focus in the industrial sector. For all of areas discussed, a reliable and well-considered IT infrastructure is necessary. Data from different sources of the shop floor need to be passed on, aggregated and analyzed. A so-called manufacturing service bus can help to standardize communication in a certain way. Ideas for such a manufacturing service bus and an implementation are, for example, presented by Schel et al. (2018) and Morariu et al. (2012). According to Morariu et al. (2012), a manufacturing service bus is used for decoupled integration of various components of the manufacturing shop floor to keep flexibility high. In companies, different department or persons are often responsible for various systems, and it is necessary for the company to meet the needs of the different responsibilities. The challenge becomes even greater with Industries 4.0 use cases and the IoT or the IIOT devices. Another approach that is discussed in this context is fog computing. Fog computing combines edge devices and cloud-like applications (Dastjerdi and Buyya, 2016) and further combines the advantage of edge devices that are close to IoT devices, such as sensors and actors, and the scalability of cloud services (Dastjerdi and Buyya, 2016). Fog computing is often located on the edge of a network (Bonomi et al., 2012).

This leads to the point that standardization is important if such an architecture is to be realized. For companies, standardization is quite challenging because flexibility is also important in the quick-changing context of Industrie 4.0, the IoT and the IIOT. A stable core infrastructure and application structure must be established, but site flexibility for new software, applications and customer needs must also be considered. Due to the broad field of topics in the digital transformation of the manufacturing industry, it is challenging for companies to evaluate which approaches are promising. However, rapid prototyping and agile software development can help them to tackle the increasingly shorter development cycles. This is leading to large changes in organizations and in the established routines of traditional companies. For communication on the industrial shop floor, two main technologies have been established. MQTT is a publish-subscribe message protocol for communication on the shop floor; it is very lightweight and can be used for devices with low computing power. OPC UA is a service-oriented architecture that supports the interoperable exchange of data. In Germany, for example, the Plattform Industrie 4.0 was founded in 2013 to answer questions regarding strategy and give suggestions to stakeholders and companies for tackling Industrie 4.0. They provide regular information about the current situation and provide advice for further action.

To standardize the communication along with the digital transformation, Plattform I 4.0 uses the Reference Architecture Model for Industrie 4.0 (RAMI 4.0) and the Asset Administration Shell to provide guidance to practitioners. RAMI 4.0 is a reference model that describes the elements to consider in Industrie 4.0 scenarios; it has three dimensions called hierarchy levels, life cycle value stream and layers (Weyrich and Ebert, 2016). The asset administration shell aims to make things interoperable (Tantik and Anderl, 2017; Wagner et al., 2017), especially in value relevant networks where products are offered as PSS. An industrial machine is built of components from different vendors. For a machine builder, it is important to know which capabilities these single components have and how data exchange from one component to another is realized. The identification of a component that provides information about its capabilities and allowing it to be identified automatically facilitates the set up and minimizes errors. This is also seen for the design and planning phase. Therefore, the concept of digital twins is becoming increasingly focused (Raineri et al., 2018; Luo et al., 2018). Other authors focus more on the manufacturing sector like Preuveneers et al. (2018) and Zambal et al. (2018). Since today there is no clear focus on one in industrial standardization model in the industry. Therefore these concepts are only adressed briefly in the presented reference architectures. For further research it should be considered which standard will win through and to integrate one ore more standards in the presented concepts.

It is important to consider also security in privacy, especially when more and more devices get connected. For large manufacturing systems often high security requirements are established. It has to be also ensured that IIOT devices on the shop floor meet with this security requirements. Offering individual and user-centric services requires the collection of personal data. Therefore privacy need to be ensured. Concepts and architectures addressing security and privacy on the shop floor should be focused more in detail. This dissertation aims in mentioning security and privacy for the relevant technologies or in the specified architectures. However no deep technical focus on security or privacy mechanisms is taken.

It is not enough to collect and process data for just the company or on-premise applications. Cloud solutions are increasingly popular, and service-oriented architectures are needed. Data from the shop floor and the enterprise level need to be published to different channels in house or in a value network. The need for centralized platforms to exchange data in value networks is emerging, but it is difficult to determine which platform will set the standard. Therefore, companies are required to provide flexible data models and deliver information to different channels. Value networks have to be considered in detail. Due to the offering of PSS in the manufacturing industry it is not always clear which participant will offer a service to the customer. For example component suppliers and machine builders aim in offering services to the end user. Further research should be performed on how value networks should be designed for PSS and how revenue models look like. Characteristics need to be elaborated to classify this value networks and give advises for practitioners.

Different reference and architectural models are presented within this dissertation. These models can be combined in further research to have a comprehensive view on the digital transformation in the manufacturing industry. Based on that maturity models can help to give guidelines for practitioners.

7 Overall conclusions

This cumulative dissertation summarizes 10 research papers, shows the relationship between them and discusses them critically. All papers contribute to the field of digital transformation in the manufacturing industry with a focus on technologies and architectures.

The first main part of the dissertation addresses predictive maintenance for industrial machines. First, an optimization model to determine the optimal number of spare parts to keep in stock is presented. Spare parts are a critical factor for the maintenance of machines. The model therefore uses condition monitoring data retrieved by a sensor, which provides actual insights into the condition of a machine and how probable a breakdown is. The required spare parts can then be added to stock in time to reduce the down time of the machine. Therefore, a new service concept is proposed in which a service provider keeps spare parts on stock for several customers and allows them to adjust the spare part required in each period for a provision fee. Another optimization model is presented where an optimal maintenance plan for several machines is the main output. In productions plants, different machines are used, which requires individual maintenance activities. Condition monitoring also provides valuable insights into the machine and required maintenance activities. To structure the topic of predictive maintenance business models, a taxonomy is developed to classify them. The business models of 113 real-world companies are analyzed according this taxonomy. A cluster analysis is performed, and the clusters are analyzed using a new visualization technique based on an autoencoder application. The result is six archetypes: hardware development, platform provider, all-in-one, information manager, consulting and analytics provider. In the second major section of the dissertation, two research papers are presented addressing installed base management in the manufacturing industry. Components and machines are used in the manufacturing industry in different scenarios and applications, and their high availability is required. A digital representation of components, machines or processes can help to address this challenge. This is also called creating a digital twin. To support digital twins, installed base management is required. An integrated installed base management system is developed within an ADR approach. Several people are involved in the ADR approach, including researchers from a German university, employees at an engineering and automation company and end users. Through iterative cycles and with the help of a focus group discussion, the final integrated installed base management system was developed, including an extensive applicability check that was performed with the help of a real-world demonstration machine. In the third major section, the focus lies on PSS and new business models in the manufacturing industry. PSS combines physical products with (smart) services, leading to disruptive changes in existing business models and the creation of new business models. To help researchers and practitioners develop PSS, a modeling framework for PSS design is proposed that utilizes the SysML. A real-world use case of a German automation and engineering company is used to show its applicability in practice. Smart services are gaining popularity along with PSS, as smart services are customer-centric and data-driven. Value cocreation between customers and smart services providers is another key factor of smart services. A structured literature analysis based on Webster and Watson (2002) is performed to structure the topic and identify research gaps. A total of 109 papers were identified and clustered into 13 topics based on a smart service life cycle. In addition, a definition for smart services is presented. The results are visualized in the form of a heat map. During the smart service literature search and analysis, knowledge management was identified as a topic to consider along with smart services. Characteristics, functional capabilities and the technical conditions of knowledge management systems for smart services are elaborated, and a reference model is further developed to show diverse designs for KMSSS. Additionally, an applicability check with a predictive maintenance use case is performed that considers a value network of component supplier, machine builder and machine operator Finally, recommendations for the design of a KMSSS are proposed. The previously discussed technologies and concepts emphasize a shift from traditional business models to service-oriented or availability-oriented business models. PSS for industrial machines are being increasingly discussed because the availability of industrial machines is essential. Vendors are asked to guarantee the availability of their machines along with the physical asset. A concept for the development of such an availability-oriented business models is validated within this dissertation. The concept has different elements, for which an industrial use case from an automation and engineering company is applied. First, personas are identified and described in detail for the mentioned use case. A customer journey is performed and the baseline set for identifying concrete scenarios and a value network. Finally, suggestions for further research are made.

An overall discussion aims in showing the relationships between the three main topics. Herein limitations of the presented research is addressed and directives for further research given. This includes also implications for practitioners to apply the presented research in practice. This dissertation shows that new technologies and future-ready IT architectures need to be established. With the help of the presented approaches changing customer needs, flexible and reliable production and new business models can be achieved.

References

Alam, Kazi Masudul; El Saddik, Abdulmotaleb (2017). “C2PS: A Digital Twin Architecture Reference Model for the Cloud-Based Cyber-Physical Systems”. In: *IEEE Access* 5, pp. 2050–2062. DOI: 10.1109/access.2017.2657006.

Apostolov, Hristo; Fischer, Matthias; Olivotti, Daniel; Dreyer, Sonja; Breitner, Michael H.; Eigner, Martin (2018). “Modeling Framework for Integrated, Model-based Development of Product-Service Systems”. In: *Procedia CIRP* 73, pp. 9–14. DOI: 10.1016/j.procir.2018.03.307.

Aronis, Kostas-Platon; Magou, Ioulia; Dekker, Rommert; Tagaras, George (2004). “Inventory control of spare parts using a Bayesian approach: A case study”. In: *European Journal of Operational Research* 154 (3), pp. 730–739. DOI: 10.1016/s0377-2217(02)00837-8.

Atzori, Luigi; Iera, Antonio; Morabito, Giacomo (2010). “The Internet of Things: A survey”. In: *Computer Networks* 54 (15), pp. 2787–2805. DOI: 10.1016/j.comnet.2010.05.010.

Baiyere, Abayomi; Cha, Jonghyuk; Ologeanu-Taddei, Roxana; Wessel, Lauri (2017). “Digital Practice Misfits: Beyond IT Artifacts”. In: *38th International Conference on Information Systems (ICIS), Seoul, Republic of Korea, December 10-13, 2017.*

Baldoni, Roberto; Mecella, Massimo; Querzoni, Leonardo (2010). “Smart Services for Home Automation. Managing Concurrency and Failures: New Wine in Old Bottles?” In: *Proceeding of the 5th International Conference on Pervasive Computing and Applications, Maribor, Slovenia, December 1-3, 2010*, pp. 1–6. DOI: 10.1109/ICPCA.2010.6112338.

Barrett, Michael; Davidson, Elizabeth; Prabhu, Jaideep; Vargo, Stephen L. (2015). “Service Innovation in the Digital Age: Key Contributions and Future Directions”. In: *MIS Quarterly* 39 (1), pp. 135–154. DOI: 10.25300/misq/2015/39:1.03.

Batubara, F. Rizal (2015). “Balancing functionality, risk, and cost in smart service networks”. In: *Proceeding of 10th International Joint Conference on Software Technologies Doctoral Consortium, Colmar, Alsace, France, July 20-22, 2015*, pp. 7–14.

Becker, Jörg; Delfmann, Patrick, eds. (2007). *Reference Modeling.* Physica-Verlag, Heidelberg, Germany. DOI: 10.1007/978-3-7908-1966-3.

Berná-Martínez, José Vicente; Maciá-Pérez, Francisco; Ramos-Morillo, Héctor; Gilart-Iglesias, Virgilio (2006). “Distributed Robotic Architecture based on Smart Services”. In: *Proceeding of the 4th IEEE International Conference on Industrial Informatics, Singapore, Singapore, August 16-18, 2006.* IEEE, pp. 480–485. DOI: 10.1109/INDIN.2006.275603.

Bock, Maximilian; Wiener, Martin (2017). “Towards a Taxonomy of Digital Business Models – Conceptual Dimensions and Empirical Illustrations”. In: *Proceedings of the 38th International Conference on Information Systems, Seoul, South Korea, December 10, 2017*.

Bockshecker, Alina; Hackstein, Sarah; Baumöl, Ulrike (2018). “Systematization of the term digital transformation and its phenomena from a socio-technical perspective – A literature review”. In: *Proceedings of the European Conference on Information Systems 2018, Portsmouth, UK , June 23-28, 2018, Paper 43*.

Bonomi, Flavio; Milito, Rodolfo; Zhu, Jiang; Addepalli, Sateesh (2012). “Fog computing and its role in the internet of things”. In: *Proceedings of the first edition of the MCC workshop on Mobile cloud computing - MCC 12, Helsinki, Finland, August 17, 2012*. ACM Press, pp. 13–16. DOI: 10.1145/2342509.2342513.

Bousdekis, Alexandros; Magoutas, Babis; Apostolou, Dimitris; Mentzas, Gregoris (2015). “Review, analysis and synthesis of prognostic-based decision support methods for condition based maintenance”. In: *Journal of Intelligent Manufacturing* 29 (6), pp. 1303–1316. DOI: 10.1007/s10845-015-1179-5.

Bouvard, K.; Artus, S.; Bérenguer, C.; Cocquempot, V. (2011). “Condition-based dynamic maintenance operations planning & grouping. Application to commercial heavy vehicles”. In: *Reliability Engineering & System Safety* 96 (6), pp. 601–610. DOI: 10.1016/j.ress.2010.11.009.

Boyes, Hugh; Hallaq, Bil; Cunningham, Joe; Watson, Tim (2018). “The industrial internet of things (IIoT): An analysis framework”. In: *Computers in Industry* 101, pp. 1–12. DOI: 10.1016/j.compind.2018.04.015.

Cellary, Wojciech (2013). “Smart governance for smart industries”. In: *Proceedings of the 7th International Conference on Theory and Practice of Electronic Governance - ICEGOV 13, Seoul, Republic of Korea, October 22-25, 2013*. ACM Press, pp. 91–93. DOI: 10.1145/2591888.2591903.

Chu, Yee-Yeen; Lin, Shih-Wei (2011). “Network Ontology and Dynamics Analysis for Collaborative Innovation in Digital Services”. In: *Proceedings of PICMET ’11: Technology Management in the Energy Smart World, Portland, OR, USA, July 31 - August 4, 2011*. IEEE, pp. 1–4.

Cohen, Morris A. (2012). “Product Performance Based Business Models: A Service Based Perspective”. In: *Proceedings of the 45th Hawaii International Conference on System Sciences, Maui, HI, USA, January 4-7, 2012*. IEEE, pp. 4814–4819. DOI: 10.1109/hicss.2012.672.

D. I. N. Deutsches Institut für Normung e. V. (2018). *DIN EN 13306:2018-02, Maintenance - Maintenance terminology; Trilingual version*. DOI: 10.31030/2641990.

Dastjerdi, Amir Vahid; Buyya, Rajkumar (2016). "Fog Computing: Helping the Internet of Things Realize Its Potential". In: *Computer* 49 (8), pp. 112–116. DOI: 10.1109/mc.2016.245.

Delfanti, Maurizio; Esposito, Giuseppe; Olivieri, Valeria; Zaninelli, Dario (2015). "SCUOLA PROJECT: the "hub of smart services" for cities and communities". In: *Proceeding of the 4th International Conference on Renewable Energy Research and Applications, Palermo, Italy, November 22-25, 2015*. IEEE, pp. 1502–1506. DOI: 10.1109/ICRERA.2015.7418658.

Dreyer, Sonja; Olivotti, Daniel; Breitner, Michael H. (2019). "Knowledge Management Systems' Design Principles for Smart Services". In: *Was submitted to: Business & Informations Systems Engineering*.

Dreyer, Sonja; Olivotti, Daniel; Lebek, Benedikt; Breitner, Michael H. (2017). "Towards a Smart Services Enabling Information Architecture for Installed Base Management in Manufacturing". In: *Proceedings of the 13th International Conference on Wirtschaftsinformatik. St. Gallen, Switzerland, February 12-15; 2017*. Ed. by J. M. Leimeister; W. Brenner, pp. 31–45.

Dreyer, Sonja; Olivotti, Daniel; Lebek, Benedikt; Breitner, Michael H. (2019). "Focusing the customer through smart services: a literature review". In: *Electronic Markets* 29 (1), pp. 55–78. DOI: 10.1007/s12525-019-00328-z.

Dreyer, Sonja; Passlick, Jens; Olivotti, Daniel; Lebek, Benedikt; Breitner, Michael H. (2018). "Optimizing Machine Spare Parts Inventory Using Condition Monitoring Data". In: *Proceedings of the Operations Research Proceedings 2016., Hamburg, Germany, August 30 - September 2, 2016*. Ed. by Andreas Fink; Armin Fügenschuh; Martin Josef Geiger. Cham: Springer International Publishing, pp. 459–465. DOI: 10.1007/978-3-319-55702-1_61.

Eickhoff, M.; Muntermann, J.; Weinrich, T. (2017). "What do FinTechs actually do? A taxonomy of FinTech business models". In: *Proceedings of the International Conference on Information Systems, Seoul, Republic of Korea, December 10-13, 2017*, pp. 1–19.

Eigner, Martin; Dickopf, Thomas; Apostolov, Hristo (2017). "System Lifecycle Management - An Approach for Developing Cybertronic Systems in Consideration of Sustainability Aspects". In: *Procedia CIRP* 61, pp. 128–133. DOI: 10.1016/j.procir.2016.11.210.

Faccio, M.; Persona, A.; Sgarbossa, F.; Zanin, G. (2014). "Industrial maintenance policy development: A quantitative framework". In: *International Journal of Production Economics* 147, pp. 85–93. DOI: 10.1016/j.ijpe.2012.08.018.

Fellmann, M.; Hucke, S.; Breitschwerdt, R.; Thomas, O.; Blinn, N.; Schlicker, M. (2011). "Supporting technical customer services with mobile devices: towards an integrated information system architecture". In: *Proceedings of the 17th Americas conference on information systems, Detroit, August 4–8, 2011, Paper 250*, pp. 1–8.

Ferretti, Stefano; D'Angelo, Gabriele (2016). "Smart Shires: The Revenge of Countrysides". In: *Proceeding of 2016 IEEE Symposium on Computers and Communication (ISCC), Messina, Italy, June 27-30, 2016*. IEEE, pp. 756–759. DOI: 10.1109/ISCC.2016.7543827.

Freitas Junior, José Carlos da Silva; Gastaud Maçada, Antonio Carlos; Brinkhues, Rafael Alfonso; Zimmermann Montesdioca, Gustavo (2016). "Digital Capabilities as Driver to Digital Business Performance". In: *Proceedings of the Twenty-second Americas Conference on Information Systems, San Diego, Carlifonia, USA, August 11-14, 2016*, pp. 1–5.

Gimpel, Henner; Rau, Daniel; Röglinger, Maximilian (2017). "Understanding FinTech start-ups – a taxonomy of consumer-oriented service offerings". In: *Electronic Markets* 28 (3), pp. 245–264. DOI: 10.1007/s12525-017-0275-0.

Gretzel, Ulrike; Sigala, Marianna; Xiang, Zheng; Koo, Chulmo (2015). "Smart tourism: foundations and developments". In: *Electronic Markets* 25 (3), pp. 179–188. DOI: 10.1007/s12525-015-0196-8.

Haider, A. (2011). "Information technologies for engineering asset management—cultural and technical barriers". In: *Proceedings of the International Conference on Information Resources Management, Seoul, Republic of Korea, June 12–14, 2011, Paper 4*.

Hamdan, Dima; Aktouf, Oum-El-Kheir; Parissis, Ioannis; Hijazi, Abbas; Sarkis, Mira; Hassan, Bachar El (2012). "SMART Service for Fault Diagnosis in Wireless Sensor Networks". In: *Proceeding of the 6th International Conference on Next Generation Mobile Applications, Services and Technologies, Paris, France, September 12-14, 2012*. IEEE, pp. 211–216. DOI: 10.1109/ngmast.2012.40.

Hartmann, Philipp Max; Zaki, Mohamed; Feldmann, Niels; Neely, Andy (2016). "Capturing value from big data – a taxonomy of data-driven business models used by start-up firms". In: *International Journal of Operations & Production Management* 36 (10), pp. 1382–1406. DOI: 10.1108/ijopm-02-2014-0098.

Hastie, Trevor; Tibshirani, Robert; Friedman, Jerome (2009). *The Elements of Statistical Learning. Data Mining, Inference, and Prediction.* Springer New York. DOI: 10.1007/978-0-387-84858-7.

Hermann, Mario; Pentek, Tobias; Otto, Boris (2016). "Design Principles for Industrie 4.0 Scenarios". In: *Proceedings of the 49th Hawaii International Conference on System Sciences, Koloa, Hawaii, HI, USA, January 5-8, 2016*. IEEE. DOI: 10.1109/hicss.2016.488.

Herterich, Matthias M.; Mikusz, Martin (2016). “Looking for a Few Good Concepts and Theories for Digitized Artifacts and Digital Innovation in a Material World”. In: *Proceedings of the 37th International Conference on Information Systems, Dublin, Ireland, December 11-14, 2016*, pp. 1–22.

Hinton, G. E.; Salakhutdinov, R. R. (2006). “Reducing the Dimensionality of Data with Neural Networks”. In: *Science* 313 (5786), pp. 504–507. DOI: 10.1126/science.1127647.

Hochreiter, Sepp; Schmidhuber, Jürgen (1997). “Long Short-Term Memory”. In: *Neural Computation* 9 (8), pp. 1735–1780. DOI: 10.1162/neco.1997.9.8.1735.

Högnelid, Pelle; Kalling, Thomas (2015). “Internet of Things and Business Models: Empirical Illustrations of How the Business Model Concept Helps Us to Understand Strategic Implications of Internet of Things Investments”. In: *Proceedings of the 2015 IEEE 9th International Conference on Standardization and Innovation in Information Technology, Sunnyvale, CA, USA, October 7-9, 2015*. IEEE. DOI: 10.1109/SIIT.2015.7535598.

Holgado, Maria; Macchi, Marco (2014). “Exploring the role of E-maintenance for value creation in service provision”. In: *Proceeding of the 2014 International Conference on Engineering, Technology and Innovation*. IEEE, pp. 1–10. DOI: 10.1109/ICE.2014.6871586.

Iivari, J. (2007). “A paradigmatic analysis of information systems as a design science”. In: *Scandinavian Journal of Information Systems* 19 (2), pp. 39–64.

Jackson, Paul J. (2015). “Networks in a Digital World: A Cybernetics Perspective”. In: *Proceedngs of the 23rd European Conference on Information Systems, Münster, Germany, May 26-19 , 2015*. DOI: 10.18151/7217364.

Jeschke, Sabina; Brecher, Christian; Meisen, Tobias; Özdemir, Denis; Eschert, Tim (2016). “Industrial Internet of Things and Cyber Manufacturing Systems”. In: *Industrial Internet of Things*. Springer International Publishing, pp. 3–19. DOI: 10.1007/978-3-319-42559-7_1.

Jin, Tongdan; Liao, Haitao (2009). “Spare parts inventory control considering stochastic growth of an installed base”. In: *Computers & Industrial Engineering* 56 (1), pp. 452–460. DOI: 10.1016/j.cie.2008.07.002.

Jürgens, Leonie; Olivotti, Daniel; Breitner, Michael H. (2019). “Einflüsse der Digitalisierung auf das Qualitätsmanagement und die Notwendigkeit einer integrierten Betrachtungsweise anhand eines Referenzmodells”. In: *IWI Discussion Paper Series* (#89).

Kaiser, K. A.; Gebraeel, N. Z. (2009). “Predictive Maintenance Management Using Sensor-Based Degradation Models”. In: *IEEE Transactions on Systems, Man, and Cybernetics*

- *Part A: Systems and Humans* 39 (4), pp. 840–849. DOI: 10.1109/tsmca.2009.2016429.

Keskin, Tayfun; Kennedy, Deanna (2015). "Strategies in Smart Service Systems Enabled Multi-sided Markets: Business Models for the Internet of Things". In: *Proceeding of the 48th Hawaii International Conference on System Sciences, Kauai, HI, USA, January 5-8, 2015*. IEEE, pp. 1443–1452. DOI: 10.1109/hicss.2015.176.

Klötzer, Christoph; Pflaum, Alexander (2017). "Toward the Development of a Maturity Model for Digitalization within the Manufacturing Industry's Supply Chain". In: *Proceedings of the 50th Hawaii International Conference on System Sciences, Waikoloa Village, Hawaii, HI, USA, January 4-7, 2017*.

Kölsch, P.; Herder, C. F.; Zimmermann, V.; Aurich, J. C. (2017). "A Novel Concept for the Development of Availability-Oriented Business Models". In: *Procedia CIRP* 64, pp. 340–344. DOI: 10.1016/j.procir.2017.03.063.

Kothamasu, Ranganath; Huang, Samuel H.; VerDuin, William H. (2006). "System health monitoring and prognostics — a review of current paradigms and practices". In: *The International Journal of Advanced Manufacturing Technology* 28 (9-10), pp. 1012–1024. DOI: 10.1007/s00170-004-2131-6.

Koukal, André; Gleue, Christoph; Breitner, Michael H. (2014). "Enhancing Literature Review Methods - Evaluation of a Literature Search Approach based on Latent Semantic Indexing". In: *Proceedings Thirty Fifth International Conference on Information Systems, Auckland, New Zealand, December 14-17, 2014*, pp. 1–20.

Kryvinska, Natalia; Strauss, Christine; Auer, Lukas; Zinterhof, Peter (2008). "Conceptual Framework for Services Creation/Development Environment in Telecom Domain". In: *Proceedings of the 10th International Conference on Information Integration and Web-based Applications & Services*, pp. 324–331. DOI: 10.1145/1497308.1497368.

Kuhn, Thomas (2017). "Digitaler Zwilling". In: *Informatik-Spektrum* 40 (5), pp. 440–444. DOI: 10.1007/s00287-017-1061-2.

Kwak, Ji-Young; Yang, Sunhee; Lee, Kyung Hee; Kim, Seon-Tae (2015). "Service-oriented networking platform on smart devices". In: *IET Communications* 9 (3), pp. 429–439. DOI: 10.1049/iet-com.2014.0312.

Lasi, Heiner; Fettke, Peter; Kemper, Hans-Georg; Feld, Thomas; Hoffmann, Michael (2014). "Industry 4.0". In: *Business & Information Systems Engineering* 6 (4), pp. 239–242. DOI: 10.1007/s12599-014-0334-4.

Lee, Byoung-Hoon; Lim, Sung-Hwa; Kim, Jai-Hoon (2010). "Scalable real-time monitoring system for ubiquitous smart space". In: *Information Processing Letters* 110 (8-9), pp. 294–299. DOI: 10.1016/j.ipl.2010.02.005.

Legner, Christine; Eymann, Torsten; Hess, Thomas; Matt, Christian; Böhmann, Tilo; Drews, Paul; Mädche, Alexander; Urbach, Nils; Ahlemann, Frederik (2017). "Digitalization: Opportunity and Challenge for the Business and Information Systems Engineering Community". In: *Business & Information Systems Engineering* 59 (4), pp. 301–308. DOI: 10.1007/s12599-017-0484-2.

Li, Youjun; Wan, Zhijiang; Huang, Jiajin; Chen, Jianhui; Huang, Zhisheng; Zhong, Ning (2015). "A Smart Hospital Information System for Mental Disorders". In: *Proceediong of the 2015 International Conference on Web Intelligence and Intelligent Agent Technology, Singapore, Singapore, December 6-9, 2015*. IEEE, pp. 321–324. DOI: 10.1109/wi-iat.2015.25.

Lin, S.; Gao, J.; Koronios, A. (2006). "Validating a data quality framework in engineering asset management". In: *Proceedings of the 17th Australasian Conference on Information Systems, Adelaide, Austrailia, December 6–8, 2006, Paper 75.*

Lindgren, R.; Henfridsson, O.; Schultze, U. (2004). "Design principles for competence management systems: a synthesis of an action research study". In: *MIS Quarterly* 28 (3), pp. 435–472. DOI: 10.2307/25148646.

Louit, Darko; Pascual, Rodrigo; Banjevic, Dragan; Jardine, Andrew K. S. (2011). "Condition-based spares ordering for critical components". In: *Mechanical Systems and Signal Processing* 25 (5), pp. 1837–1848. DOI: 10.1016/j.ymssp.2011.01.004.

Luo, Weichao; Hu, Tianliang; Zhu, Wnedan; Tao, Fei (2018). "Digital twin modeling method for CNC machine tool". In: *Proceedings of the 2018 IEEE 15th International Conference on Networking, Sensing and Control*, pp. 1–4. DOI: 10.1109/ICNSC.2018.8361285.

Malhotra, Pankaj; Vig, Lovekesh; Shroff, Gautam; Agarwal, Puneet (2015). "Long short term memory networks for anomaly detection in time series". In: *Proceedings of the European Symposium on Artificial Neural Networks, Computational Intelligence and Machine Learning., Bruges, Belgium, April 22-24*. Presses universitaires de Louvain, pp. 89–94.

Markus, M. Lynne; Loebbecke, Claudia (2013). "Commoditized Digital Processes and Business Community Platforms: New Opportunities and Challenges for Digital Business Strategies". In: *MIS Quarterly* 37 (2), pp. 649–654.

Matt, Christian; Hess, Thomas; Benlian, Alexander (2015). "Digital Transformation Strategies". In: *Business Information Systems Engineering* 57 (5), pp. 339–343. DOI: 10.1007/s12599-015-0401-5.

Mert, G.; Herder, C. F.; Menck, N.; Aurich, J. C. (2016). "Innovative Services for Customized, Availability-oriented Business Models for the Capital Goods Industry". In: *Procedia CIRP* 47, pp. 501–506. DOI: 10.1016/j.procir.2016.03.223.

Morariu, Cristina; Morariu, Octavian; Borangiu, Theodor; Raileanu, Silviu (2012). "Manufacturing Service Bus Integration Model for Implementing Highly Flexible and Scalable Manufacturing Systems". In: *IFAC Proceedings Volumes* 45 (6), pp. 1850–1855. DOI: 10.3182/20120523-3-ro-2023.00433.

Mukudu, Nyasha; Ventura, Neco; Mwangama, Joyce; Elmangoush, Asma; Steinke, Ronald; Magedanz, Thomas (2016). "Prototyping Smart City Applications over Large Scale M2M Testbed". In: *Proceedings of the IST Africa Conference 2016, Durban, South Africa, May 11-13, 2016*, pp. 1–11. DOI: 10.1109/ISTAFRICA.2016.7530666.

Neff, Alexander A.; Hamel, Florian; Herz, Thomas Ph.; Uebernickel, Falk; Brenner, Walter (2013). "Developing a Maturity Model for Product-Service Systems in Manufacturing Enterprises". In: *Proceedings of the 17th Pacific Asia Conference on Information Systems, Jeju Island, Republic of Korea, June 18-22, 2013*. Vol. 144.

Negri, Elisa; Fumagalli, Luca; Macchi, Marco (2017). "A Review of the Roles of Digital Twin in CPS-based Production Systems". In: *Procedia Manufacturing* 11, pp. 939–948. DOI: 10.1016/j.promfg.2017.07.198.

Nickerson, Robert C.; Varshney, Upkar; Muntermann, Jan (2013). "A method for taxonomy development and its application in information systems". In: *European Journal of Information Systems* 22 (3), pp. 336–359. DOI: 10.1057/ejis.2012.26.

Nuaimi, Eiman Al; Neyadi, Hind Al; Mohamed, Nader; Al-Jaroodi, Jameela (2015). "Applications of big data to smart cities". In: *Journal of Internet Services and Applications* 6 (1), pp. 1–15. DOI: 10.1186/s13174-015-0041-5.

Nwankpa, Joseph K.; Roumani, Yaman (2016). "IT Capability and Digital Transformation: A Firm Performance Perspective". In: *Proceedings of the 37th International Conference on Information Systems, Dublin, Ireland, December 11-14, 2016*, pp. 1–16.

Oh, Jeong Seok; Park, Jang Sik; Kwon, Jeong Rock (2010). "Ubiquitous Infrastructure and Smart Service on City Gas Environments in Korea". In: *Proceeding of the 5th International Conference on Future Information Technology, Busan, South Korea, May 21-23, 2010*, pp. 1–5. DOI: 10.1109/FUTURETECH.2010.5482730.

Oliva, R.; Kallenberg, R. (2003). "Managing the transition from products to services". In: *International Journal of Service Industry Management* 14 (2), pp. 160–172. DOI: 10.1108/09564230310474138.

Olivotti, Daniel; Dreyer, Sonja; Kölsch, Patrick; Herder, Christoph Felix; Breitner, Michael H.; Aurich, Jan C. (2018). "Realizing availability-oriented business models in the capital goods industry". In: *Procedia CIRP* 73, pp. 297–303. DOI: 10.1016/j.procir.2018.03.299.

Olivotti, Daniel; Dreyer, Sonja; Lebek, Benedikt; Breitner, Michael H. (2018). "Creating the foundation for digital twins in the manufacturing industry: an integrated installed base management system”. In: *Information Systems and e-Business Management* 17 (1), pp. 89–116. DOI: 10.1007/s10257-018-0376-0.

Olivotti, Daniel; Passlick, Jens; Axjonow, Alexander; Eilers, Dennis; Breitner, Michael H. (2018). “Combining Machine Learning and Domain Experience: A Hybrid-Learning Monitor Approach for Industrial Machines”. In: *Lecture Notes in Business Information Processing. Exploring Service Science*. Vol. 331. Springer International Publishing, pp. 261–273. DOI: 10.1007/978-3-030-00713-3_20.

Olivotti, Daniel; Passlick, Jens; Dreyer, Sonja; Lebek, Benedikt; Breitner, Michael H. (2018). “Maintenance Planning Using Condition Monitoring Data”. In: *Operations Research Proceedings*. Springer International Publishing, pp. 543–548. DOI: 10.1007/978-3-319-89920-6_72.

Olivotti, Daniel; Rickenberg, Tim A.; Breitner, Michael H. (2014). “Car Sharing in Zürich - Optimization and Evaluation of Station Location and Size”. In: *Proceedings of the Multikonferenz Wirtschaftsinformatik 2014, Paderborn, Germany, February 26-28, 2014*.

Osmundsen, Karen; Iden, Jon; Bygstad, Bendik (2018). “Digital Transformation: Drivers, Success Factors and Implications”. In: *Proceedings of the 12th Mediterranean Conference on Information Systems (MCIS), Korfu, Greece, 28-30 September, 2018*.

Osterwalder, Alexander; Pigneur, Yves (2010). *Business Model Generation*. Wiley John + Sons. 288 pp.

Pagani, Margherita (2013). “Digital Business Strategy and Value Creation: Framing the Dynamic Cycle of Control Points”. In: *MIS Quarterly* 37 (2), pp. 617–632. DOI: 10.25300/misq/2013/37.2.13.

Paluch, Stefanie; Wünderlich, Nancy V. (2016). “Contrasting risk perceptions of technology-based service innovations in inter-organizational settings”. In: *Journal of Business Research* 69 (7), pp. 2424–2431. DOI: 10.1016/j.jbusres.2016.01.012.

Pao, Sheng-Ying; Reben, Alexander J.; Rayes, Ammar (2011). “MoSS: Mobile Smart Services for Ubiquitous Network Management”. In: *Proceeding of 2011 International Conference on Collaboration Technologies and Systems, Philadelphia, PA, USA, May 23-27, 2011*. IEEE, pp. 48–52. DOI: 10.1109/CTS.2011.5928664.

Passlick, Jens; Dreyer, Sonja; Olivotti, Daniel; Grützner, Lukas; Breitner, Michael H. (2019). “Predictive Maintenance as an Internet of Things enabled Business Model: Toward a Taxonomy”. In: *Submitted to: Electronic Markets*.

Passlick, Jens; Dreyer, Sonja; Olivotti, Daniel; Lebek, Benedikt; Breitner, Michael H. (2018). “Assessing Research Projects: A Framework”. In: *IWI Discussion Paper Series* (#83).

Peng, Ying; Dong, Ming; Zuo, Ming Jian (2010). “Current status of machine prognostics in condition-based maintenance: a review”. In: *The International Journal of Advanced Manufacturing Technology* 50 (1-4), pp. 297–313. DOI: 10.1007/s00170-009-2482-0.

Perera, Charith; Zaslavsky, Arkady; Christen, Peter; Georgakopoulos, Dimitrios (2013). “Sensing as a service model for smart cities supported by Internet of Things”. In: *Transactions on Emerging Telecommunications Technologies* 25 (1), pp. 81–93. DOI: 10.1002/ett.2704.

Perl, Jossef; Daskin, Mark S. (1985). “A warehouse location-routing problem”. In: *Transportation Research Part B: Methodological* 19 (5), pp. 381–396. DOI: 10.1016/0191-2615(85)90052-9.

Preuveneers, Davy; Joosen, Wouter; Ilie-Zudor, Elisabeth (2018). “Robust Digital Twin Compositions for Industry 4.0 Smart Manufacturing Systems”. In: *2018 IEEE 22nd International Enterprise Distributed Object Computing Workshop (EDOCW)*. IEEE, pp. 69–78. DOI: 10.1109/edocw.2018.00021.

Raineri, Ivan; Mura, Francesco La; Giberti, Hermes (2018). “Digital Twin Development of HexaFloat, a 6DoF PKM for HIL Tests”. In: *Mechanisms and Machine Science*. Springer International Publishing, pp. 258–266. DOI: 10.1007/978-3-030-03320-0_28.

Rosemann M, Vessey I. (2008). “Toward improving the relevance of information systems research to practice: the role of applicability checks”. In: *MIS Quarterly* 32 (1), pp. 1–22. DOI: 10.2307/25148826.

Ross, Jeanne W.; Sebastian, Ina M.; Beath, Cynthia; Mocker, Martin; Moloney, Kate G.; Fonstad, Nils O. (2016). “Designing and Executing Digital Strategies”. In: *Proceedings of the 37th International Conference on Information Systems, Dublin, Ireland. December 11-14, 2016*, pp. 1–17.

Sakurada, Mayu; Yairi, Takehisa (2014). “Anomaly Detection Using Autoencoders with Nonlinear Dimensionality Reduction”. In: *Proceedings of the MLSDA 2014 2nd Workshop on Machine Learning for Sensory Data Analysis - MLSDA14, Gold Coast, Australia, December 1-5, 2014*. ACM Press. DOI: 10.1145/2689746.2689747.

Salema, Maria Isabel Gomes; Barbosa-Povoa, Ana Paula; Novais, Augusto Q. (2007). “An optimization model for the design of a capacitated multi-product reverse logistics network with uncertainty”. In: *European Journal of Operational Research* 179 (3), pp. 1063–1077. DOI: 10.1016/j.ejor.2005.05.032.

Schel, Daniel; Henkel, Christian; Stock, Daniel; Meyer, Olga; Rauhöft, Greg; Einberger, Peter; Stöhr, Matthias; Daxer, Marc Andre; Seidelmann, Joachim (2018). “Manufacturing Service Bus: An Implementation”. In: *Procedia CIRP* 67, pp. 179–184. DOI: 10.1016/j.procir.2017.12.196.

Schröder, Werner E.; Sagadin, Jochen (2013). “Das Management des Produktionsfaktors Anlage – Von der betrieblichen Instandhaltung zur ganzheitlichen integrierten Anlagenbewirtschaftung”. In: *BHM Berg- und Hüttenmännische Monatshefte* 158 (7), pp. 274–277. DOI: 10.1007/s00501-013-0155-7.

Schrödl H.and Bensch, S. (2013). “E-Procurement of Cloud-based Information Systems – a Product Service System Approach”. In: *Proceedings of the Thirty Fourth International Conference on Information Systems, Milan, Italy, December 15-18, 2013*, pp. 1–19.

Sebastian, Ina M.; Mocker, Marin; Ross, Jeanne W.; Moloney, Kate G.; Beath, Cynthia; Fonstad, Nils O. (2017). “How Big Old Companies Navigate Digital Transformation”. In: *Mis Quarterly Executive* 16 (3), pp. 197–213.

Sein, M. K.; Henfridsson, O.; Purao, S.; Rossi, M.; Lindgren, R. (2011). “Action design research”. In: *MIS Quarterly* 35 (1), pp. 37–56. DOI: 10.2307/23043488.

Sokal, R. R.; Michener, C. D. (1985). “A statistical method for evaluating systematic relationships”. In: *University of Kansas Bulletin* 38 (22), pp. 1409–1438.

Sonneberg, Marc-Oliver; Kühne, Kathrin; Breitner, Michael H. (2015). “Decision Support System for the Optimization of Electric Car Sharing Stations”. In: *Proceedings of the 36th International Conference on Information Systems, Fort Worth, Texas, USA, December 13-16, 2015*.

Stoll, Ines; Olivotti, Daniel; Breitner, Michael H. (2018). “Digitalisierung im Einkauf: Eine Referenzarchitektur zur Veränderung von Organisation und Prozessen”. In: *IWI Discussion Paper Series* (#86).

Strüker, Jens; Kerschbaum, Florian (2012). “From a Barrier to a Bridge: Data-Privacy in Deregulated Smart Grids”. In: *Proceeding of the 33rd International Conference on Information Systems, Orlando, Florida, USA,* pp. 1–16.

Susto, Gian Antonio; Beghi, Alessandro; Luca, Cristina De (2012). “A Predictive Maintenance System for Epitaxy Processes Based on Filtering and Prediction Techniques”. In: *IEEE Transactions on Semiconductor Manufacturing* 25 (4), pp. 638–649. DOI: 10.1109/tsm.2012.2209131.

Tantik, Erdal; Anderl, Reiner (2017). “Integrated Data Model and Structure for the Asset Administration Shell in Industrie 4.0”. In: *Procedia CIRP* 60, pp. 86–91. DOI: 10.1016/j.procir.2017.01.048.

Tao, Fei; Zhang, Meng (2017). “Digital Twin Shop-Floor: A New Shop-Floor Paradigm Towards Smart Manufacturing”. In: *IEEE Access* 5, pp. 20418–20427. DOI: 10.1109/access.2017.2756069.

Tianyong, Wang; Zhengliang, Xu; Ge, Gao (2006). “Development and Strategy of Knowledge Management for E-services”. In: *Proceeding of the 2006 International Conference* *on Service Systems and Service Management, Troyes, France, October 25-27, 2006.* IEEE, pp. 30–35. DOI: 10.1109/ICSSSM.2006.320584.

Tuán, Anh Lê; Quoc, Hoan N. Mau; Soldatos, John; Papaioannou, Thanasis; Serrano, Karl Aberer Martin; Hauswirth, Manfred (2012). "Global Sensor Modeling and Constrained Application Methods enabling Cloud-Based Open Space Smart Services". In: *Proceeding of 9th International Conference on Ubiquitous Intelligence and Computing and 9th International Conference on Autonomic and Trusted Computing, Fukuoka, Japan, September 4-7, 2012.* IEEE, pp. 196–203. DOI: 10.1109/UIC-ATC.2012.165.

Uhlemann, Thomas H.-J.; Lehmann, Christian; Steinhilper, Rolf (2017). "The Digital Twin: Realizing the Cyber-Physical Production System for Industry 4.0". In: *Procedia CIRP* 61, pp. 335–340. DOI: 10.1016/j.procir.2016.11.152.

Waeyenbergh, Geert; Pintelon, Liliane (2002). "A framework for maintenance concept development". In: *International Journal of Production Economics* 77 (3), pp. 299–313. DOI: 10.1016/s0925-5273(01)00156-6.

Wagner, C.; Epple, U.; Grothoff, J.; Drath, R.; Hoffmeister, M.; Malakuti, S.; Grüner, S.; Zimmermann, P. (2017). "The role of the industry 4.0 asset administration shell and the digital twin during the life cycle of a plant". In: *Proceedings of the 22nd IEEE international conference on emerging technologies and factory automation, Limassol, September 12–15*, pp. 1–8. DOI: 10.1109/ETFA.2017.8247583.

Wang, Ling; Chu, Jian; Wu, Jun (2007). "Selection of optimum maintenance strategies based on a fuzzy analytic hierarchy process". In: *International Journal of Production Economics* 107 (1), pp. 151–163. DOI: 10.1016/j.ijpe.2006.08.005.

Ward, Joe H. (1963). "Hierarchical Grouping to Optimize an Objective Function". In: *Journal of the American Statistical Association* 58 (301), pp. 236–244. DOI: 10.1080/01621459.1963.10500845.

Weber, Christian; Königsberger, Jan; Kassner, Laura; Mitschang, Bernhard (2017). "M2DDM – A Maturity Model for Data-Driven Manufacturing". In: *Procedia CIRP* 63, pp. 173–178. DOI: 10.1016/j.procir.2017.03.309.

Weber, Mario; Boban, Marija (2016). "Security Challenges of the Internet of Things". In: *Proceedings of the 2017 IEEE Conference on Wireless Sensors, Miri, Malaysia, November 13-14, 2017*, pp. 638–643. DOI: 10.1109/ICWISE.2017.8267153.

Webster, Jane; Watson, Richard T. (2002). "Analyzing the past to prepare for the future: Writing a Literature Review". In: *MIS Quarterly* 26 (2), pp. xiii–xxiii.

Weyrich, Michael; Ebert, Christof (2016). "Reference Architectures for the Internet of Things". In: *IEEE Software* 33 (1), pp. 112–116. DOI: 10.1109/ms.2016.20.

Wildeman, R. E.; Dekker, R.; Smit, A. C. J. M. (1997). “A dynamic policy for grouping maintenance activities”. In: *European Journal of Operational Research* 99 (3), pp. 530–551. DOI: 10.1016/s0377-2217(97)00319-6.

Wortmann, Felix; Flüchter, Kristina (2015). “Internet of Things”. In: *Business & Information Systems Engineering* 57 (3), pp. 221–224. DOI: 10.1007/s12599-015-0383-3.

Wünderlich, N. V.; Wangenheim, F. v.; Bitner, M. J. (2013). “High Tech and High Touch: A Framework for Understanding User Attitudes and Behaviors Related to Smart Interactive Services”. In: *Journal of Service Research* 16 (1), pp. 3–20. DOI: 10.1177/1094670512448413.

Yang, Kelei; Niu, Xiaozi (2009). “Research on the spare parts inventory”. In: *Proceedings of the 16th International Conference on Industrial Engineering and Engineering Management, Beijing, China, October 21-23, 2009*. IEEE, pp. 1018–1021. DOI: 10.1109/icieem.2009.5344253.

Yu, Chien-Chih (2004). “A Web-Based Consumer-Oriented Intelligent Decision Support System for Personalized E-Services”. In: *Proceedings of the 6th international conference on Electronic commerce (ICEC), Delft, The Netherlands, October 25 - 27, 2004*, pp. 429–437. DOI: 10.1145/1052220.1052274.

Zambal, Sebastian; Eitzinger, Christian; Clarke, Michael; Klintworth, John; Mechin, Pierre-Yves (2018). “A digital twin for composite parts manufacturing : Effects of defects analysis based on manufacturing data”. In: *2018 IEEE 16th International Conference on Industrial Informatics (INDIN)*. IEEE, pp. 803–808. DOI: 10.1109/indin.2018.8472014.

Appendix

A Optimizing Machine Spare Parts Inventory

Appendix A

Optimizing Machine Spare Parts Inventory Using Condition Monitoring Data

Sonja Dreyer, Jens Passlick, Daniel Olivotti, Benedikt Lebek and Michael H. Breitner

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Abstract:
In the manufacturing industry, storing spare parts means capital commitment. The optimization of spare parts inventory is a real issue in the field and a precise forecast of the necessary spare parts is a major challenge. The complexity of determining the optimal number of spare parts increases when using the same type of component in different machines. To find the optimal number of spare parts, the right balance between provision costs and risk of machine downtimes has to be found. Several factors are influencing the optimum quantity of stored spare parts including the failure probability, provision costs and the number of installed components. Therefore, an optimization model addressing these requirements is developed. Determining the failure probability of a component or an entire machine is a key aspect when optimizing the spare parts inventory. Condition monitoring leads to a better assessment of the components failure probability. This results in a more precise forecast of the optimum spare parts inventory according to the actual condition of the respective component. Therefore, data from condition monitoring processes are considered when determining the optimal number of spare parts.

Keywords: Spare parts, Sensor data, Industrial machines

B Maintenance Planning Using Condition Monitoring Data

Appendix B

Maintenance Planning Using Condition Monitoring Data

Daniel Olivotti, Jens Passlick, Sonja Dreyer, Benedikt Lebek and Michael H. Breitner

Citation: Olivotti, Daniel; Passlick, Jens; Dreyer, Sonja; Lebek, Benedikt; Breitner, Michael H. (2018). "Maintenance Planning Using Condition Monitoring Data". In: Operations Research Proceedings 2017., Berlin, Germany, September 6 - 8, 2017. Ed. by Natalia Kliewer; Jan Fabian Ehmke; Ralf Borndörfer. Operations Research Proceedings. Cham: Springer International Publishing, pp. 543–548.

DOI: 10.1007/978-3-319-89920-6_72

Abstract:
Maintenance activities of machines in the manufacturing industry are essential to keep machine availability as high as possible. A breakdown of a single machine can lead to a complete production stop. Maintenance is traditionally performed by predefined maintenance specifications of the machine manufacturers. With the help of condition-based maintenance, maintenance intervals can be optimized due to detailed knowledge through sensor data. This results in an adapted maintenance schedule where machines are only maintained when necessary. Apart from time savings, this also reduces costs. An decision support system with optimization model for maintenance planning is developed considering the right balance between the probabilities of failure of the machines and the potential breakdown costs. The current conditions of the machines are used to forecast the necessary maintenance activities for several periods. The decision support system helps maintenance planners to choose their decision-making horizon flexibly.

Keywords: Predictive maintenance, Condition-based maintenance, Condition monitoring, Machine availability, Sensor data

C A Hybrid-Learning Monitor Approach

Appendix C

Combining Machine Learning and Domain Experience: A Hybrid-Learning Monitor Approach for Industrial Machines

Daniel Olivotti, Jens Passlick, Alexander Axjonow, Dennis Eilers and Michael H. Breitner

Citation: Olivotti, Daniel; Passlick, Jens; Axjonow, Alexander; Eilers, Dennis; Breitner, Michael H. (2018). "Combining Machine Learning and Domain Experience: A Hybrid-Learning Monitor Approach for Industrial Machines". In: Lecture Notes in Business Information Processing. Exploring Service Science. Vol. 331. Springer International Publishing, pp. 261–273.

DOI: 10.1007/978-3-030-00713-3_20

Abstract:
To ensure availability of industrial machines and reducing breakdown times, a machine monitoring can be an essential help. Unexpected machine downtimes are typically accompanied by high costs. Machine builders as well as component suppliers can use their detailed knowledge about their products to counteract this. One possibility to face the challenge is to offer a product-service system with machine monitoring services to their customers. An implementation approach for such a machine monitoring service is presented in this article. In contrast to previous research, we focus on the integration and interaction of machine learning tools and human domain experts, e.g. for an early anomaly detection and fault classification. First, Long Short-Term Memory Neural Networks are trained and applied to identify unusual behavior in operation time series data of a machine. Second, domain experts are confronted with related monitoring data, e.g. temperature, vibration, video, audio etc., from different sources to assess and classify anomaly types. With an increasing knowledge base, a classifier module automatically suggests possible causes for an anomaly automatically in advance to support machine operators in the anomaly identification process. Feedback loops ensure continuous learning of the anomaly detector and classifier modules. Hence, we combine the knowledge of machine builders/component suppliers with application specific experience of the customers in the business value stream network.

Keywords: Machine monitoring, Hybrid learning, Long Short-Term Memory neural networks, Product-Service-Systems

D Predictive Maintenance Taxonomy

Appendix D

Predictive Maintenance as an Internet of Things enabled Business Model: Towards a Taxonomy

Jens Passlick, Sonja Dreyer, Daniel Olivotti, Lukas Grützner and Michael H. Breitner

Submitted

Abstract:
Predictive maintenance (PdM) as an important application of the Internet of things (IoT) is discussed in many companies, especially in the manufacturing industry. PdM uses data, usually sensor data, to optimize maintenance activities. This study develops a taxonomy for the classification of PdM business models. The taxonomy enables a comparison and analysis of PdM business models. Business models of 113 companies are described with the developed taxonomy. With a cluster analysis six archetypes are identified and discussed. The three archetypes hardware development, analytics provider, and all-in-one are most frequently represented in the data set. For the analysis of the clusters, a new visualization procedure is used which consists of an autoencoder application. The analysis enables practitioners to discuss their own business models and those of other companies. The implication that an IoT architecture is an influential differentiator for PdM business models is important for further research.

Keywords: Predictive maintenance, Business models, Taxonomy

Introduction

The introduction of the Internet of things (IoT) is currently the subject of intense discussion both in practice and scientifically (Whitmore et al. 2015). Not only the private but also the industrial environment that is changing through the IoT is discussed. The term industrial internet of things (IIoT) is also used here. Predictive maintenance (PdM) is one way of using the IIoT to create value. PdM means using data, especially sensor data of IoT devices, to optimize maintenance activities. Often this also includes the term “Condition Monitoring”. The aim of PdM is not to carry out maintenance unnecessarily early, but also not too late. This includes being able to make forecasts about the further deterioration of e.g., a machine. Especially unscheduled deterioration can also be detected to proactively take action.

The consulting firm PricewaterhouseCoopers, in cooperation with Mainnovation, came to the conclusion that out of 280 surveyed companies from Germany, Belgium and the Netherlands, 132 companies might want to implement a PdM solution and 52 companies are already working on such an implementation (PricewaterhouseCoopers 2017). This shows the relevance for companies. The relevance of PdM is also increasing in the scientific field (Daily & Peterson 2017). However, it is difficult for companies to get an overview of the market situation of PdM offers. Which providers are on the market and what do they offer? Previous research in the IoT environment has already shown that understanding the business models of company partners is important for long-term success (Dijkman et al. 2015). Also for a scientific discussion of PdM business models, it is important to get an overview of different forms of PdM business models to better understand how PdM business models work in practice. Companies can better locate their own business models on the market and identify potential growth opportunities. This results in the following research question (RQ), which we address in our research:

RQ: Which elements of PdM business models are important and which characteristics are interrelated on the market?

The article proceed as follows: First we will describe how we define a PdM business model. Based on this, we develop a taxonomy for PdM business models using a procedure according to Nickerson et al. (2013). We then use the final taxonomy to classify the business models of 113 companies. Based on this classification, we conduct a cluster analysis and build archetypes that represent typical PdM business models. The results are analyzed and discussed. Further, implications and limitations are outlined and further research is suggested.

Predictive Maintenance and Related Literature

A comprehensive insight into the current condition of a component or machine is necessary for PdM (Sipos et al. 2014). More abstract, the key for PdM is data (Borgi et al. 2017). Usually, a central server is used to collect, transmit and process the data (Wang et al. 2017). Monitoring and determining the current state of equipment is the first step of PdM (Hui et al. 2008). The beginning of degradation must be detected as early as possible (Borgi et al. 2017, Khazraei and Deuse 2011). It must be possible to extract all information that is necessary for reliable PdM. Sensors are a source for condition-related data (Sipos et al. 2014). As data collection in (near) real-time is necessary, control tools can be used that are capable of collecting data automatically from several components and systems (Aivaliotis et al. 2017). Data do not only have to be collected but also must be analyzed (Cachada et al. 2018). Tools for data analysis do not only process sensor data but also take the maintenance history, operational data, design and application into account (Darwanto et al. 2012). Indicators must be identified, measured and modelled so that activities can be derived from that (Groba et al. 2007). Vibration analysis, thermal images (Barbera et al. 1996), trend analysis and simulation (Aivaliotis et al. 2017) are exemplary techniques that are used. The described elements are summarized in general IoT architectures (e.g., Chen 2013, Turber et al. 2014).

The fact that system's downtimes are minimized through PdM leads to a reduction of production losses (Baidya and Ghosh 2015, Spendla et al. 2017, Zoll et al. 2018). In contrast to regularly performed maintenance activities, PdM takes the current condition of the system into account (Chu et al. 1998). This leads to a reduction of maintenance activities (Last et al. 2010, Susto et al. 2013). Maintenance activities are performed as late as possible, under the condition that the system is still running in its intended way (Mattes and Scheibelhofer 2012). The probability of extensive failures is reduced (Darwanto et al. 2012). From an economic perspective, costs are reduced because of less and precise maintenance activities as well as lower probabilities of default (Wang et al. 2009). Additionally, the customer experience is increased and the customer loyalty is strengthened (Gerloff and Cleophas 2017).

In the literature, maintenance activities are often classified, mostly regarding their intervention point. It reflects that the definition of PdM is not standardized. Önel et al. (2009) say that there are not more than two types of maintenance: breakdown and preventive maintenance. Richter et al. (2017) differentiate between reactive, predictive and proactive maintenance activities. Thereby, predictive does only mean that warnings are displayed, without subsequent action. Susto et al. (2012) see PdM as the highest expansion of maintenance activities. The first step is reactive maintenance, followed by preventive and condition based maintenance. Condition-based maintenance is different from PdM because only the current condition is the basis for decisions. In contrast, prediction tools and methods are used in PdM (Susto et al. 2012). In another article condition-based maintenance and PdM are equated (Last et al. 2010). Another point of view describes PdM as the aggregation of condition-based and prognostic-based maintenance (Araiza 2004). Mustakerov and Borissova (2013) name condition-based maintenance the highest expansion that combines preventive and PdM with real-time monitoring. The other way round, Groba et al. (2007) argue that PdM is based on the concept of condition monitoring. The presentation of You (2017) goes in the same direction. Further, the author sees a temporal development from reactive maintenance over condition-based monitoring to PdM. Khazraei and Deuse (2011) mention avoidance-based, condition-based, and detective-based maintenance as tactics within PdM. The definition of PdM is therefore different in the details. In the present article, we define PdM as the most comprehensive form of maintenance that includes condition-based maintenance and further types of maintenance that are enabled by data analysis.

Although there are many articles dealing with PdM there is not yet a comprehensive taxonomy available. A taxonomy enables a better understanding of PdM business models as one concrete example of an IoT use case. The individual elements of the business models can be identified and their relations examined (Glass & Vessey 1995). Taxonomies have already been developed in related topics. Hartmann et al. (2016) develop a taxonomy for startups of data-driven business models, Täuscher and Laudien (2018) examine platform business models and two different FinTech startup taxonomies are provided by Gimpel et al. (2017) and Eickhoff et al. (2017). Different maintenance strategies are already classified but not as detailed as it is possible within a taxonomy. A taxonomy shows how diverse PdM offers are by considering existing offers from companies all over the world.

Taxonomy Development

Procedure

In developing our taxonomy, we have oriented on Nickerson et al. (2013). The term “taxonomy” is defined as “a set of it n dimensions Di (i=1, ..., n) each consisting of ki (ki>2) mutually exclusive and collectively exhaustive characteristics […].” (Nickerson et al. 2013, p. 340). Starting from the analysis of scientific literature on business models, the dimensions of the taxonomy are derived conceptually. Subsequently, related characteristics are developed by empirically examining a large number of globally distributed companies active in PdM. During the development of the taxonomy, the focus is usually on a certain area of interest, which is determined as a meta characteristic at the beginning of the process. This meta characteristic is a superordinate and abstract description of the area on which the taxonomy focuses, and serves as the basis for the choice of dimensions and characteristics in the taxonomy. In our case, the meta characteristic is to define elements of PdM business models. The taxonomy development takes place in several iterations (Nickerson et al. 2013). In each iteration a different approach is conceivable. Either the taxonomy is adapted based on concepts (conceptual-to-empirical), usually existing models, or on empirical data (empirical-to-conceptual). Figure 1 shows this procedure. The characteristics assigned to a company, according to the definition of Nickerson et al. (2013), can be seen as exclusive. Exclusive means that in each dimension exactly one characteristic is assigned to a company. After each iteration, a decision is made on the basis of various end conditions whether a further iteration is necessary. The end conditions used were adapted from Nickerson et al. (2013) (see Appendix, Table 5). The following section describes the steps performed in each iteration.

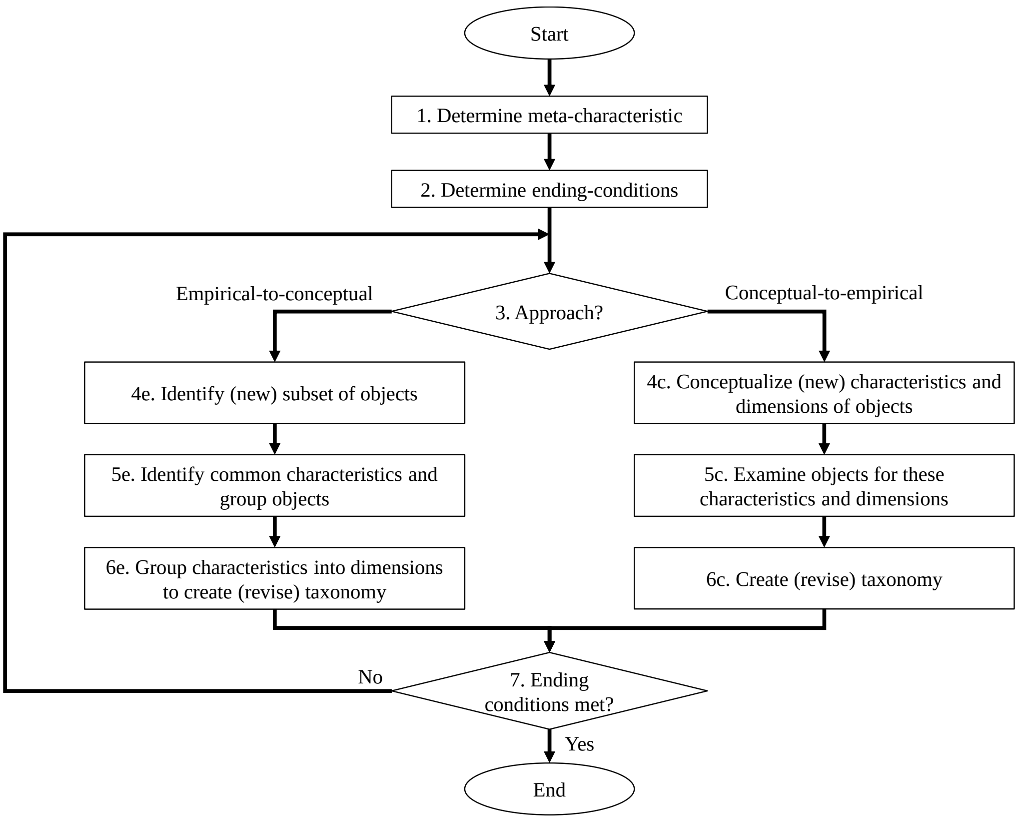


Figure 1 Taxonomy development procedure by Nickerson et al. (2013)

Iterations

In the first iteration, the approach was conceptual-to-empirical. Based on the analysis of literature on business models, existing knowledge was reviewed and key terms relevant to our taxonomy were identified. We compared electronic business model elements by Afuah and Tucci (2001), Alt and Zimmermann (2001), Brousseau and Penard (2007), Mahadevan (2000), Osterwalder and Pigneur (2010). The Business Model Canvas by Osterwalder and Pigneur (2010) summarizes the majority of the elements of business models in the literature. Additionally, the Business Model Canvas is highly regarded in practice. Therefore, it forms the basis for our taxonomy. Possible dimensions were discarded in which many PdM business models are similar (e.g., key resources) and dimensions where no relevant information is available (cost structures, key partners). According to Osterwalder and Pigneur (2010), the element sales channels is about which methods are used to sell a product or service and how customers are reached. These include, for example, the use of Internet marketplaces or the direct use of sellers. Further, revenue streams was included to answer the question which payment models are offered to customers. Pay users once for a complete product or a monthly use fee for a specific service? To describe the type of customers, the dimension customer segment was also included. At the end of the first iteration this resulted in the following dimensions: key activities, value proposition, revenue streams, sales channel, and customer segment. Several end conditions of the taxonomy development were not fulfilled after the first iteration (see Appendix, Table 5), therefore a further iteration was necessary.

In the second iteration, the approach was empirical-to-conceptual and data from real PdM business models were analyzed. To this purpose, we conducted 42 interviews with representatives of various companies at the “Hannover Industrie Messe” 2018, a leading fair for industrial automation and IT technologies. We have discussed different topics on various aspects of the company (can be found in the appendix). The survey was prepared on the basis of the previously discussed knowledge about business models and the results of the first iteration of the taxonomy development. The length of the interviews was between five minutes and 40 minutes, on average about 15 minutes. In addition, Google was used to search for PdM companies using search terms including “Companies”, “Predictive Maintenance” and “Condition Monitoring”. Webpages with lists of companies which have PdM business models were found there. This resulted in a database of 71 companies after conducting the interviews and the Google search. We then used the Crunchbase website (a database containing various information about companies, started to track start-ups) to search for appropriate companies. Further, we used a Crunchbase base account to download the open data map. In the file, containing information about the companies, the terms "predictive maintenance" and "condition monitoring" were used for a search in the short descriptions. Thereby, 42 additional companies were identified, which resulted in 113 companies in our entire database (can be seen in the Appendix, Table 7).

Initially, a random sample of ten companies was examined from which suitable characteristics for the dimensions obtained in the first iteration were derived. Similar characteristics were summarized to a single characteristic. For example, chemical, food, automotive, steel, and others were combined in the *manufacturing industry* characteristic. The production of various hardware components from the fields of sensor technology, electronics, networking, and machines was combined to *hardware development*. Data analysis and the digital representation of this data were combined to *condition monitoring*. In addition, during this empirical iteration, it was found that the taxonomy requires a further dimension called *clients*, which complements important characteristics missing in the dimension *customer segment*. It turned out that IoT respectively PdM business models can be differentiated according to the customers to be addressed by the company. For example, some companies have customers who again sell to other companies (*B2B2B*). Further, it was recognized that another differentiation characteristic is the technical layer to which a company refers with its offer. This refers to the layers as described by IoT architecture models (e.g., Chen 2013, Turber et al. 2014). The models usually consist of four levels from the recording to the analysis of the data. Such models are used to describe the different prerequisites that are necessary for machine to machine communication. In the business model context it allows conclusions on which layer a company offers a solution. The end conditions of the taxonomy were not reached due to the newly identified dimensions and characteristics. Furthermore, the taxonomy showed a significant change.

The approach in the third iteration was again empirical-to-conceptual. A larger random sample of 20 other companies was examined to check whether the dimensions and characteristics of the first two iterations were stable enough (i.e. sufficient number and chosen meaningfully). This iteration combined the provision of infrastructures, platforms and software in a public cloud. The development of algorithms for the analysis of data sets and their representation, as well as the development of programs for data security, encryption, and secure communication via the internet are based on the development of mathematical algorithms. These are written programs and therefore similar to each other. So, the newly identified characteristic development of security software was added to the already existing characteristic *software development*. Customer segments such as military, healthcare, etc. were combined into *high security areas*. The largest changes during this iteration step occurred in the dimension revenue stream. It was found that the revenue stream dimension is not entirely accurate for this taxonomy, as the definition provided by Osterwalder and Pigneur (2010) was too imprecise for our taxonomy. In order to describe this dimension more precisely, it was reformulated into *payment model*. In addition, payment models consisting of a combination of several models, such as *one-time payment*, *project* payment, and/or subscription (payment on *time basis*), were combined to *hybrid*. Furthermore, the new characteristic payment on *usage basis* was identified and added to the taxonomy, which is similar to the already existing characteristic payment on *time basis*. In contrast to *time basis*, *usage basis* is billing based on the use of a particular resource (e.g., used computing capacity). In addition, the dimension sales channel was reformulated to *deployment channel*. It was found that a better differentiator is how a customer accesses a service than how it is bought. In the third iteration there was also a significant change in the taxonomy, indicating that the end conditions are not met.

Further 30 companies are examined according to the empirical-to-conceptual approach. It turns out that large companies such as Bosch Rexroth or National Instruments cannot be assigned to a single key activity because they are active in many different areas (consulting, hardware development, software development, etc.). Accordingly, the activities of such companies were combined in *universal range*. Furthermore, the newly identified customer segments logistics, aviation and railway were combined in *logistics/transport industry*, as these segments are similar in their scope. A further customer segment, a combination of *manufacturing industry + energy sector* was identified and added to the taxonomy. In the fourth iteration there was no significant change in the taxonomy, but some characteristics were added, so all end conditions of the taxonomy development are not yet fulfilled.

Finally, the 53 remaining companies in the sample are examined. During this investigation no further dimensions or characteristics were added or changed. Thus, according to Nickerson et al. (2013), the five subjective as well as the eight objective end conditions of the taxonomy development were considered to be fulfilled. Formally, the final taxonomy was exactly the same as the taxonomy after the fourth iteration step.

The Developed Predictive Maintenance Business Model Taxonomy

In the following, we present the final version of the developed taxonomy. Table 1 shows the found dimensions in the first column and the identified characteristics in the respective rows. The first dimension *key activity* describes what the company does primarily according to its business model (Osterwalder et al. 2005, Osterwalder & Pigneur 2010). The second dimension *value promise* describes how customer needs are satisfied and customer problems are solved (Osterwalder et al. 2005, Osterwalder & Pigneur 2010). The dimension *payment model* is defined by how the performance of a PdM provider is measured and billed. For example, the characteristic *project* expresses that it is paid for the execution of a defined project. This is therefore likely to be found frequently in consulting. On the other hand, *time basis* is billed for a certain period of time. For example, for a one month use of a cloud platform. But it is also possible to pay according to the actual use (*usage basis*), for example according to the computing power used. How a product or service is provided to the customer is represented in the dimension *deployment channel*. In order to distinguish the companies according to their *customer segments*, the dimension describes the branch in which the company mainly has its customers (Osterwalder et al. 2005, Osterwalder & Pigneur 2010). The dimension *clients* describes to which type of customer a service is sold. The last dimension *information layer* represents the area a service of the company is provided. The idea for this dimension is based on Chen (2013). The definition of the characteristics of each dimension can be found in Table 6 of the Appendix.

Table 1 Developed taxonomy

Dimensions	**Characteristics**		
Key activities	1) Hardware development	2) Software development	3) Consulting
	4) Edge computer development	5) Provision of a public cloud	6) Hardware retailer
	7) Universal range	8) Provision of an application platform	
Value promise	1) All-in-one solution	2) Condition monitoring	3) Connectivity
	4) Automation	5) Forecasting	6) Data security
	7) Data storage + software development tools		
Payment model	1) One-time sales	2) Time basis	3) Project
	4) Usage basis	5) Hybrid	
Deployment channel	1) Physically	2) www	3) Physically + www (cloud)
	4) www (cloud) + API	5) www (cloud)	6) Physically + www (cloud) + API
Customer segment	1) Manufacturing industry	2) Energy sector	3) No industry focus
	4) High-security areas	5) Manu. industry + energy sector	6) Manu. industry + Logistics/Transport Industry
Clients	1) B2B	2) B2B + B2B2B	3) B2B + state
Information layer	1) Application and services	2) Information handling	3) Information delivering layer
	4) Object sensing and information gathering layer	5) Multiple	

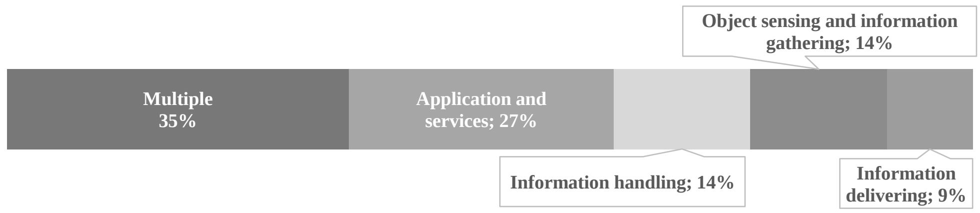
Taxonomy Application

Mapping of the Sample

In order to show the usability of the taxonomy, we assigned all 113 companies of the dataset to their respective characteristics. For all companies, the company website was used as the basis for the mapping. Companies that were identified on the fair website were supplemented with information from the interviews with company representatives. If the Crunchbase database served as a source, first information could be obtained from the short description provided. The mapping of the characteristics of the data set was divided among the authors. In the case of borderline companies, the assignment of further authors was checked. Table 2 shows the distribution in each dimension.

Table 2 Distribution of the characteristics

Dimensions	Distribution
Key activities	Universal 21%; Software 20%; Application platform 18%; Consulting 14%; Hardware 13%; Edge 10%; Retailer; 2%; Public cloud; 2%
Value promise	Condition monitoring 29%; Forecasting 24%; All-in-one 23%; Connectivity 9%; Storage + software development; 8%; Automation; 5%; Security 2%
Payment model	Hybrid 36%; Time basis 25%; One-time sales 19%; Project 14%; Usage basis; 6%
Deployment channel	Physically 35%; Physically + www (cloud); 28%; www (cloud) 14%; www (cloud) + API 10%; www 8%; Physically + www (cloud) + API; 4%

Dimensions	Distribution
Customer segment	
Clients	
Information layer	

The dimension *key activity* shows that the different characteristics are relatively evenly distributed with the exception of the characteristics *hardware retailer* and *public cloud offering*. This might be related to the fact that providers of such services do not explicitly advertise a PdM offer and were therefore not part of our data set. The *value promise* is dominated by *condition monitoring*, *forecasting* and *all-in-one solutions*. *Data security* is only weakly represented, which could be due to the fact that companies that specialize in security do not explicitly advertise PdM services. With regard to the *payment model* dimension, it is noticeable that payment on a usage basis still plays a subordinate role. Most companies use *hybrid* forms of payment. In the *deployment channel* dimension, it is noticeable that the *physical* provision of products plays a major role alongside *cloud and software* offerings. Most companies do not have an explicit sector focus. If companies concentrate, they focus primarily on the manufacturing *industry*. The desired business of PdM providers is primarily in a *B2B* environment. An explicit focus on *state* or government organizations is rare. In the *information layer* dimension, about one third of the companies have an offer for several layers. Many companies have offers on the *application and services* layer.

Business Model Clusters

In order to gain a better understanding of the PdM market, we have created archetypes in the PdM environment equivalent to other developments of business model taxonomies (Gimpel et al. 2017, Eickhoff et al. 2017). To this end, we conducted a cluster analysis. Since we have almost identical requirements as in the article by Gimpel et al. (2017), we have also used the Ward's (1963) algorithm for clustering. Ward's (1963) algorithm is a hierarchical cluster algorithm with the advantage that not only a predefined number of clusters are formed, but all possible ones (Gimpel et al. 2017, Backhaus et al. 2011). We have also used the Sokal and Michener (1958) matching coefficient as a distance measure. As Gimpel et al. (2017) describe, there are now various algorithms with which the suitable number of clusters can be determined. Depending on the algorithm, the results can be quite different. For this reason, we first take a graphical look at the result of the Ward algorithm (Täuscher & Laudien 2018). It is shown in Figure 2. Three different clusters can be identified at the first, upper two branches. After looking at the companies assigned to the respective clusters, the groups can be named with the following three labels: "Universal vendors", "Software and platforms", "Hardware and consulting". From our point of view this naming showed that the groups were not yet granular enough. The next branching would lead to four groups. Since the height and thus the distance of the groups is close to the next two branches, we did not analyze four, but six groups in the next step. These groups are marked red in Figure 2.

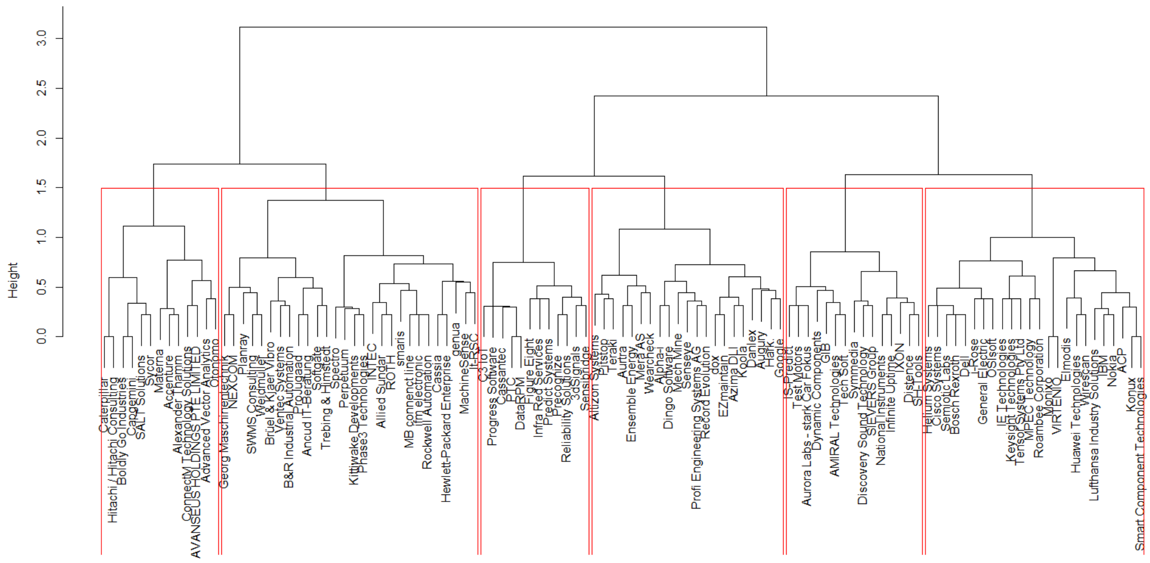


Figure 2 Result of the Ward clustering visualized by a dendrogram

After analyzing the companies of the six different groups, we come to the following labels for the clusters formed: "Consulting", "Hardware development", "Platform provider", "Information manager", "Analytics provider", and "All-in-one". We then examined a subdivision into seven groups. However, this rather leads to a deterioration of the cluster results. So we came to the conclusion that a subdivision into six groups is the most reasonable. In addition to hierarchical cluster algorithms, partitioning algorithms are also available for the final allocation of companies to the six clusters. Following the approach of Hartmann et al. (2016), we look at a cluster creation using the k-means and the k-medoids algorithms. The k-medois has the advantage that it does not react as strongly to outliers as the k-means algorithm (Hartmann et al. 2016). The decision on the quality of the assignment of the two algorithms was made by analyzing the distribution of the characteristics in each group. Like in the research by Hartmann et al. (2016), the k-medoids algorithm leads to better results which are shown in Table 3.

Table 3 shows the clear differentiation of the formed groups in the first dimension (*key activities*). At least 61% of a group were assigned to the same characteristic. Based on the *key activities* we also named the groups. For the archetypes four and six, we have also included other dimensions in the naming, especially the second and seventh dimension. The *hardware development* group also includes some of the companies that develop *edge devices*. The main value proposition (D2) is *condition monitoring*, but *automation and connectivity* also play a role. The business is mainly conducted through *one-time sales* (D3) and therefore the *deployment channel* (D4) is *physical*. Most companies do not have a specific industry focus, but if so in the *manufacturing industry*. Customers are mainly in the *B2B* segment. All companies that explicitly mention the *state* as a customer are part of the *hardware development* group. The majority of companies work on the *object sensing and information gathering* layer.

The *platform provider* group comprises vendors of application platforms (D1) with a focus on *forecasting* models (D2). They enable these developments with a *hybrid payment model* (D3). Since some vendors do this in combination with *consulting* services and special *hardware devices*, the *deployment channel* (D4) is both *physical* and via a *cloud* platform. In this group a focus on the manufacturing *industry* can be seen (D5). The customers are in the *B2B* environment (D6) and the companies mainly operate in the *application and services* layer (D7).

Table 3 Results of the cluster analysis

		Hardware development	*Platform provider*	*All-in-one*	*Information manager*	*Consulting*	*Analytics provider*
		1	2	3	4	5	6
D1	Provision of an application platform		64%	6%		7%	35%
	Edge computer development	17%		10%	67%		
	Hardware development	63%					
	Hardware retailer	8%					
	IT consulting			6%	17%	87%	
	Provision of a public cloud			3%			4%
	Software development	8%	21%	6%	17%	7%	61%
	Universal range	4%	14%	68%			
D2	Automation	17%	7%			7%	
	Data storage + software development tools	4%		13%	17%		13%
	All-in-one solution	8%		55%	17%	27%	9%
	Forecasting	8%	57%	3%	17%	20%	52%
	Data security	8%					
	Connectivity	13%	14%	13%		7%	
	Condition monitoring	42%	21%	16%	50%	40%	26%
D3	Usage basis		21%	6%		7%	4%
	Time basis		7%	19%	17%		87%
	One-time sales	83%		3%			
	Hybrid	13%	64%	71%	83%		9%
	Project	4%	7%			93%	
D4	Physically	83%		13%	33%	87%	4%
	Physically + www (cloud)	4%	36%	65%	50%		13%
	Physically + www (cloud) + API	4%		10%		7%	
	www	8%	14%	3%	17%		13%
	www (cloud)		36%	3%			43%
	www (cloud) + API		14%	6%		7%	26%
D5	Energy sector	8%	7%	3%	17%		9%
	High-security areas	4%					
	Industry	29%	57%	16%	67%	33%	22%
	Industry + energy sector	8%	14%	13%	17%	7%	
	Industry + logistics/transport industry	4%	7%	6%		7%	9%
	No industry focus	46%	14%	61%		53%	61%
D6	B2B	71%	71%	74%	67%	67%	83%
	B2B + B2B2B	17%	29%	26%	33%	27%	17%
	B2B + State	13%				7%	
D7	Application and services		71%	6%		60%	43%
	Information delivering	17%		3%	33%		13%
	Information handling	4%	21%	13%		7%	30%
	Multiple	25%		74%	50%	33%	13%
	Object sensing and information gathering	54%	7%	3%	17%		

Note: Due to rounding inaccuracies, the sum of a column in a dimension is not always exactly 100%.

Various activities are offered by companies which are assigned to the *all-in-one* group (D1). Mainly they promise an *all-in-one* solution (D2). Their *payment model* is *hybrid* (D3) and the *deployment channel* is both *physical* and via *cloud* solutions (D4). There is no specific customer segment (D5) and the customers are in the B2B environment (D6). The companies are active on all information layers (D7). The *all-in-one* group is the largest group in the investigated data set.

In contrast, the *information manager* group is the smallest one in the data set. In this group there are mainly companies that *develop edge devices,* but also *software development* and *consulting* play a role (D1). The most common *value promise* is the realization of *condition monitoring* (D2). The *payment model* (D3) and the *deployment channel* (D4) are equal to the *all-in-one* group (*hybrid and physically + www (cloud)*). In the *information manager* group there is a focus on *industrial* companies (D5). The group's customers are not only *B2B* customers, but one third also constitute *B2B2B* relationships (D6). Half of the companies are active on *multiple* information layers. Another third takes care of the *information delivering* (D7).

We call the fifth cluster the *consulting* group. Obviously the *key activity here* is *consulting* (D1). The *value proposition* is *condition monitoring* (D2) and the payment is *project*-based (D3). Above all, consulting services are sold. Since a consulting service cannot currently be provided automatically via a cloud or software, the *deployment channel* is primarily *physically* (D4). There is no special customer focus (D5) and *B2B* customers are addressed (D6). The consulting is mainly done in the area of *application and services* but one third of the companies operate on *multiple* layers (D7).

The last group *analytics provider* mainly deals with *software development* but also the *provision of application platforms* plays a role (D1). The *value promise* lies above all in the creation of *forecasts* (D2). The billing takes place on a *time basis* (D3) and the provision of a service via *cloud* (D4). There is no industry focus (D5) and the users are *B2B* customers (D6). Mostly, companies are active on the *application and services* layer, but *information handling* is also often found. The groups described are summarized in Table 4.

Table 4 Found PdM business model archetypes

	Archetype					
	1	**2**	**3**	**4**	**5**	**6**
Label	*Hardware development*	*Platform provider*	*All-in-one*	*Information manager*	*Consulting*	*Analytics provider*
Key activities	Hardware development	Provision of an application platform	Universal offer	Edge computer development	Consulting	Software development
Value promise	Condition monitoring	Forecasting	All-in-one solution	Condition monitoring	Condition monitoring	Forecasting
Payment model	One-time sales	Hybrid	Hybrid	Hybrid	Project	Time basis
Deployment channel	Physically	Physically + www (cloud)	Physically + www (cloud)	Physically + www (cloud)	Physically	www (cloud)
Customer segment	No industry focus	Manufacturing industry	No industry focus	Manufacturing Industry	No industry focus	No industry focus
Clients	B2B	B2B	B2B	B2B + B2B2B	B2B	B2B
Information layer	Object sensing and information gathering	Application and services	Multiple	Multiple & information delivering	Application and services	Application and services & information handling
Share in sample (113)*	21%	12%	27%	5%	13%	20%
Example company	Rockwell Automation	Test Motors	National Instruments	IXON	Hitachi Consulting	Senseye

*Due to rounding inaccuracy the sum is not exactly 100%

In order to better understand the different groups and their connections between each other, we visualize the firms in a two-dimensional coordinate system. Representing all characteristics of the firms in a two-dimensional space requires a dimensionality reduction technique which takes into account the dependencies and possible non-linear relationships between them. In this paper we use an autoencoder with three hidden layers (10-2-10 neurons) which uses all characteristics of the firms as input features (Hinton 2006). The structure of hidden neurons compresses the information of the input to two dimensions in the latent space of the network which can be used for a two-dimensional scatter plot. Figure 3 shows the resulting representation. Each firm is visualized by a dot in the coordinate system while the color indicates the affiliation of the firms based on the k-medois clustering.

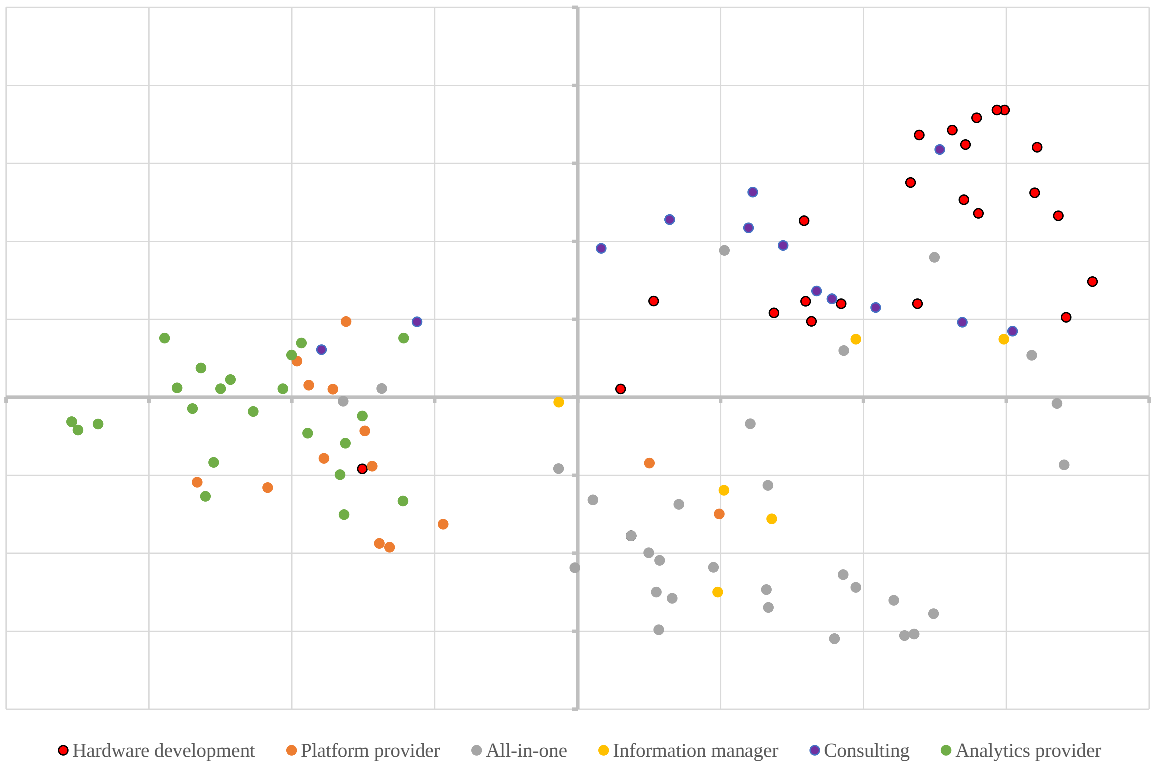


Figure 3 Visualization of the clustering using an autoencoder method

Initially, three large groups can be identified in the visualization. In the range x<-0.2, in the quadrant x>0, y<0 and the group x, y > 0. In our analysis, we found that the composition of these three groups is approximately 80% consistent with the allocation of the three largest groups of the Ward algorithm, as shown in Figure 2. It can be seen that companies of the *all-in-one* group are represented in all areas. This shows that there are generalists with different focuses. Nevertheless, the companies of this group are clustered in one point, because the companies usually distinguish themselves from the other groups by the first two dimensions, *key activities* and *value promise*. A similarity between companies in the *analytics and platform provider* groups can also be seen. This coincides with our experience in assigning the characteristics and is shown in table 4. Both groups are primarily concerned with the creation of *forecasts*, both operate in the *application and software* layer and either *software development* or the use of software or a *cloud platform* is sold. The groups *consulting* and *hardware development* also seem to be similar. On closer inspection, however, it can be seen that the distances are much greater than between *analytics* and *platform provider*. In both groups, companies have *condition monitoring* as the majority *value promise* and *physically* as *deployment channel*. However, the dimension *information layer* expresses the fact that the companies in the respective groups have different offers.

Discussion, Implications, and Recommendations

The cluster analysis has shown the PdM business model archetypes which are currently practiced. A similarity to the archetypes found during the investigation of data-driven business models is noticeable (Hartmann et al. 2016). When considering data-driven business models, the data source plays a decisive role in addition to general aspects of a business model like the key activities or the value promise. The data source plays small role in the developed taxonomy, since the data comes from the respective customers. Instead, the business models can be differentiated according to layers of an IoT architecture. But also in the data driven business models there is a distinction between “data-aggregation-as-a-service” and “analytics-as-a-service” similar to the archetypes *platform and analytics provider* found in this study (Täuscher & Laudien 2018). *Analytics providers* offer the analysis of customer data and develop software for this purpose, while *platform providers* only provide the prerequisites for further analyses. The *analytics provider* does not only act on the *application and services* layer, but takes also care of the *information handling*. In addition to these archetypes, there are also hardware developers, consultants and generalists in the PdM environment. When considering the sample companies assigned to the archetype *hardware development*, we found companies (e.g., ROTH) that address the problem that older machines are not yet internet-capable. Here hardware is needed to enable further analysis for PdM. In parallel, the presence of the *all-in-one* archetype supports the insight by Dijkman et al. (2015) that it is important for IoT business models to be convenient, usable and “getting the job done” (Dijkman et al. 2015, p. 676). *All-in-one* offers seem to address this demand. For example, in addition to the software for analyzing the collected data, the company National Instruments supplies various monitoring devices for recording different sensors. The existence of consulting firms shows that certain use cases are complex and/or additional resources are needed for realizing PdM use cases.

The developed taxonomy allows an initial classification of a concrete IoT business model, namely a PdM business model. It was found that many elements of the taxonomy are similar to other taxonomies. For example, there are often the dimensions *value proposition* and *key activities* (e.g., Hartmann et al. 2016, Eickhoff et al. 2017, Täuscher & Laudien 2018). However, the respective characteristics and the dimension *information layer* are different. The differentiation of the sample companies according to the IoT layers was important in order to identify the differences between the individual PdM business models.

Our research also has implications for practice. Information about which dimensions are important when considering PdM business models are provided by the taxonomy. It allows companies to classify their own business model and the models of other companies facilitating a comparison. The found archetypes support these comparisons. Companies can also use the archetypes to identify whether their PdM offering is rare or common on the market. This assessment simplifies a specialization. But also companies that simply want to use PdM services can profit from the results of our research. As Dijkman et al. (2015) have already concluded for IoT business models, it is important for companies to understand how others make money in the ecosystem. The results of our study contribute to the understanding of PdM business models and thus companies can optimize their networks or ecosystems.

The archetypes *hardware development*, *analytics provider, and all-in-one* are most strongly represented in the investigated data sample. In contrast, there are few companies of the *information manager* type. There could be three reasons for this: First, there are currently few companies that pursue such a business model. This would mean that there is still a gap in the market that offers growth opportunities for companies. Second, there are many companies with a similar business model, but they do not promote this offer under the terms “condition monitoring” and “predictive maintenance”. For such companies, extended or modified marketing could make sense. Third, there is no demand for it because companies do not need specific solutions or use their own solutions.

Visualizing the assigned sample companies using an autoencoder offers, besides using a dendrogram, another possibility to visualize the similarities of the companies. In our case the dendrogram was better suited to identify a meaningful number of groups, while the two dimensional chart better represents the distances and overlaps of the respective groups. From our experience, a combination of both methods is an efficient approach for the formation and interpretation of archetypes.

Limitations and Further Research

In addition to the knowledge gained from this research, the limitations of this research must also be mentioned. The taxonomy depends on the definition of PdM. On the basis of existing literature, we comprehensively defined PdM and regarded for example “condition monitoring” as a part of PdM. If PdM is defined differently, a different taxonomy results. The size of the used sample is limited. This is particularly evident in the cluster analysis when analyzing the cluster *information manager*. Only 5% of the sample were assigned to this cluster, which makes the cluster very small and therefore hardly interpretable. Further research with more data is desirable in this area as it simplifies the description and thus the analysis of this archetype.

The sample also only includes companies that can be found under the terms “predictive maintenance” or “condition monitoring”. There can be companies that have a PdM-like offer, but do not name it explicitly and thus cannot be found. We have tried to counteract this by using overview online articles as a source for the companies under investigation. However, many companies in these articles have explicitly used the PdM term as well. Also, some companies describe only roughly what their offers look like. We have tried to counter this problem through the analysis of borderline companies by several authors.

The newly used visualization with the partial use of an autoencoder procedure is a first attempt to visualize the assignment of business models according to a taxonomy. In our case, this has led to interesting insights and made the PdM market transparent. Further research is needed to gain more experience with this process and to determine whether it can provide useful insights generally.

Our research is only a momentary snapshot. Especially the found archetypes must be checked again after a certain time, because the market is dynamic and changes are conceivable. Furthermore, new technologies have the potential to significantly change the market situation. Thus, the taxonomy will also change over time. Additional characteristics may be added and even the consideration of further dimensions can become necessary. But then our taxonomy offers a starting point for further development.

Conclusions

Our research presents a taxonomy for the classification of PdM business models. It is the basis for a classification of different providers of PdM solutions. To create the taxonomy, a data set of 113 companies was examined. In a further step, the business models were described on the basis of the taxonomy. Using a cluster analysis it could be examined which archetypes of PdM business models currently exist. Six different archetypes were identified. The analysis of the archetypes shows that not only the general business model dimensions of the Business Model Canvas (Osterwalder & Pigneur 2010) are important for the differentiation, but also the inclusion of an IoT architecture (Chen 2013). There are PdM offers for all four layers of the architecture, whereby the layer information delivering is underrepresented in the data set examined. Although PdM services are very diverse, our study has shown that PdM business models can be divided into six archetypes. This insight allows in theory and practice to better understand PdM business models.

In addition to the findings about the PdM business models, a partially applied autoencoder procedure was used to visualize the assigned business models. This was valuable to better understand the different archetypes and their relationships. In combination with a dendrogram, this visualization enabled an analysis of the clusters formed. The procedure can be transferred to other studies and contributes to an efficient analysis there.

Appendix

Content of the Interviews

The following points were addressed in the interviews:

- Company name
- Position in the company (of the interviewee)
- Key activities
- Payment model
- Sales channel
- Customers
- Customer segment
- Value proposition for the customer
- Return of Invest for the customer
- Opinion regarding the expected market development

Iterations and End Conditions

Table 5 Summary of fulfilled end conditions per iteration based on Nickerson et al. (2013)

Iteration					Ending conditions
1. con.*	**2. emp.***	**3. emp.***	**4. emp.***	**5. emp.***	
	x	x	x	x	Concise
	x	x	x	x	Robust
			x	x	Comprehensive
x	x	x	x	x	Extendible
				x	Explanatory
				x	All objects or a representative sample of objects have been examined
x	x	x	x	x	No object was merged with a similar object or split into multiple objects in the last iteration
	x	x	x	x	At least one object is classified under every characteristics of every dimension
				x	No new dimensions or characteristics were added in the last iteration
				x	No dimensions or characteristics were merged or split in the last iteration
x	x	x	x	x	Every dimension is unique and not repeated (i.e., there is no dimension duplication)
	x	x	x	x	Every characteristic is unique within its dimension (i.e., there is no characteristic duplication within a dimension)
	x	x	x	x	Each cell (combination of characteristics) is unique and is not repeated (i.e., there is no cell duplication)

*con. = conceptual, emp. = empirical

Definitions of the Characteristics Used

Table 6 Dimensions, characteristics and their definitions

Dim.	Characteristic	Definition
D1 – Key activities	1) Hardware development	Hardware development describes the development and manufacture of technical machine elements.
	2) Software development	Software development describes the development/adaptation of programs of data processing systems.
	3) Consulting	Advising companies on the design, implementation and improvement of processes and solutions.
	4) Edge computer development	It describes the development of systems for decentralized data acquisition/data processing at the edge of the network (also called "Fog Computing"). Can occur in combination with the use of a cloud. Can include both software and hardware development, but with a clear focus on edge computing.
	5) Provision of a public cloud	Provision of a computing and/or storage infrastructure accessible via the internet.
	6) Hardware retailer	Purchases hardware components from various smaller manufacturers and distributes them to larger companies (occurs mainly in Asia; smaller, less well-known manufacturers use this to sell their products globally).
	7) Universal range	Broadly based businesses with multiple key areas of activity.
	8) Provision of an application platform	An application platform is a framework of services on which applications depend for standard operations. The platform includes operating systems, execution services, data services, cloud services and development tools.
D2 – Value promise	1) All-in-one solution	Includes complete software and hardware solutions from sensors to data storage to data analysis.
	2) Condition monitoring	Storage, analysis and display of machine data in real time (data must be provided).
	3) Connectivity	Provision of hardware and software components for setting up systems (e.g., routers, network cables, etc.).
	4) Automation	Provision of hardware components that enable the transfer of functions of the production process from humans to artificial systems (e.g., sensors). Components that enable a "retrofit".
	5) Forecasting	Forecast of machine or component lifetimes or lifetimes of a machine part (e.g., section, component).
	6) Data security	Includes the provision of security technology in the areas of hardware and software (e.g., fire-resistant hardware components, encryption programs, etc.) for the implementation of predictive maintenance.
	7) Data storage + software development tools	Provides large amounts of disk space and tools to create, debug, diagnose, and manage software.
D3 – Payment model	1) One-time sales	Product/service is paid once.
	2) Time basis	Product/service is paid for on the basis of its usage period or at regular intervals (e.g., subscription or license for one year).
	3) Project	Product/service is paid within the scope of a project, after the project no further costs are charged for the service provided or for owning the developed output.
	4) Usage basis	Product/service is paid on the basis of the amount of services used, the number of uses, the computing needs, etc.
	5) Hybrid	Combination of two or more payment models.
D4 – Deployment channel	1) Physically	Provision of the product/service/hardware takes place physically (e.g., by implementing/installing software or hardware on site, consulting, etc.).
	2) www	Product/service can be downloaded or used via the Internet.
	3) Physically + www (cloud)	Combination of physical provision of products/services (see description "physical") and use of services on a cloud accessible via the Internet.
	4) www (cloud) + API	Use of the product/service on a cloud accessible via the Internet. A programming interface is also provided.
	5) www (cloud)	Use of the product/service on a cloud accessible via the Internet.
	6) Physically + www (Cloud) + API	Combination of previous characteristics (see above).
D5 – Customer segment		A more detailed definition of the segments is not necessary.

Dim.	Characteristic	Definition
D6 – Clients	1) B2B	Selling products, services or products to other companies. No sales to end customers.
	2) B2B + B2B2B	Combination of B2B (see above) and Business-to-Business-to-Business (B2B2B). B2B2B is a B2B activity in which the customer of the company in question sells platform services to other companies (e.g., a company rents platform services and then sells them as services in addition to its product).
	3) B2B + State	Companies sell products/services to customers in the public sector (e.g., military). This occurs in combination with B2B (see above).
D7 – Information layer	1) Application and services	Applications and services that use the acquired data (e.g., sensor data), e.g., for an analysis or forecast of the future deterioration of a machine (Chen 2013).
	2) Information handling	Processing of data and/or provision of computing capacity (Chen 2013)
	3) Information delivering layer	Transport and/or networking of information (Chen 2013).
	4) Object sensing and information gathering layer	Provision of sensors, data extraction and/or collection of information (Chen 2013).
	5) Multiple	When activities take place on more than one layer.

Predictive Maintenance Companies Sample

Table 7 Company sample with name of the company, website, and source

Company	Website	Source
3dSignals	http://www.3dsig.com	Crunchbase Predictive Maintenance
Accenture	https://www.accenture.com/us-en/service-accenture-corrosion-management-services	Website List
ACP	https://www.acp.de	Hannover Industrie Messe 2018
Advanced Vector Analytics	http://www.ava-labs.com/	Crunchbase Condition Monitoring
Alexander Thamm	https://www.alexanderthamm.com/de/	Website List
Allied Sundar	http://www.sundar.com.tw/	Hannover Industrie Messe 2018
Alpha-i	http://alpha-i.co/	Crunchbase Predictive Maintenance
Altizon Systems	http://altizon.com/	Crunchbase Webpage Search
AMIRAL Technologies	https://www.amiraltechnologies.com/en/	Hannover Industrie Messe 2018
Ancud IT-Beratung	https://www.ancud.de/	Hannover Industrie Messe 2018
Augury	http://www.augury.com	Crunchbase Predictive Maintenance
Aurora Labs - stark Car Fokus	https://www.auroralabs.com/	Crunchbase Webpage Search
Aurtra	https://www.aurtra.com.au	Crunchbase Condition Monitoring
AVANSEUS HOLDINGS PTE LIMITED	http://www.avanseus.com/	Crunchbase Predictive Maintenance
Azima DLI	http://www.azimadli.com	Crunchbase Condition Monitoring
B&R Industrial Automation	https://www.br-automation.com/	Hannover Industrie Messe 2018
Boldly Go Industries	https://www.boldlygo.de	Hannover Industrie Messe 2018
Bosch Rexroth	https://www.boschrexroth.com/en/xc/service/industrial-applications/predictive-maintenance/predictive-maintenance-2	Website list
Brüel & Kjaer Vibro	https://www.bkvibro.com	Hannover Industrie Messe 2018
C3 IoT	https://c3iot.ai/	Crunchbase Webpage Search
Capgemini	https://www.capgemini.com	Hannover Industrie Messe 2018
Cassantec	https://casantec.com/	Website List
Cassia	https://www.cassianetworks.com/	Hannover Industrie Messe 2018
Caterpillar	https://www.cat.com/de_DE/support/maintenance/condition-monitoring.html	Website List
Cisco Systems	https://www.cisco.com/c/en/us/solutions/internet-of-things/overview.html	Website List
ConnectM Technology Solutions	http://www.connectm.com	Crunchbase Condition Monitoring

Company	Website	Source
Danlex	http://www.danlex.com	Crunchbase Predictive Maintenance
DataRPM	http://www.datarpm.com/	Crunchbase Webpage Search
Dell	http://www.dell.com/en-us/work/learn/internet-of-things-solutions#Why-choose-Dell?	Website List
Dingo Software	http://www.dingo.com	Crunchbase Predictive Maintenance
Discovery Sound Technology	http://www.discoverysoundtechnology.com	Crunchbase Predictive Maintenance
Distence	https://www.distence.fi/de	Hannover Industrie Messe 2018
dox	http://dox.tech	Crunchbase Predictive Maintenance
Dynamic Components	http://www.dynamic-components.de	Crunchbase Predictive Maintenance
Elmodis	http://www.elmodis.com/	Crunchbase Webpage Search
Ensemble Energy	http://www.ensembleenergy.ai	Crunchbase Predictive Maintenance
EZmaintain	https://www.ezmaintain.com	Crunchbase Predictive Maintenance
Figure Eight	https://www.figure-eight.com/	Crunchbase Webpage Search
General Electric	https://www.ge.com/digital/sites/default/files/Predix-from-GE-Digital-Overview-Brochure.pdf	Website List
genua	https://www.genua.de	Hannover Industrie Messe 2018
Georg Maschinentechnik	http://www.georg-maschinentechnik.de/	Hannover Industrie Messe 2018
GIB	https://www.gibmbh.de/en/	Hannover Industrie Messe 2018
Google	https://cloud.google.com/	Hannover Industrie Messe 2018
Hark.	https://harksys.com	Crunchbase Predictive Maintenance
Helium Systems	https://www.helium.com/solutions/manufacturing	Website List
Hewlett-Packard Enterprise	https://www.hpe.com/de/de/solutions/industrial-internet-of-things.html	Hannover Industrie Messe 2018
Hitachi / Hitachi Consulting	https://www.hitachiconsulting.com/solutions/hitachi-predictive-maintenance.html	Website List
Huawei Technologies	https://e.huawei.com/en/solutions/business-needs/enterprise-network/agile-iot/elevators-connection	Website List
IBM	https://www.ibm.com/us-en/marketplace/ibm-predictive-maintenance-optimization	Website List
IE Technologies	http://www.ietechnologiesllc.com	Crunchbase Predictive Maintenance
ifm electronic	https://www.ifm.com/	Website List
Infinite Uptime	http://www.infinite-uptime.com/	Crunchbase Webpage Search
Infra Red Services	http://www.infraredservices.com.au	Crunchbase Condition Monitoring
INTEC	https://www.intec-connectivity.com/	Hannover Industrie Messe 2018
i-Rose	http://www.i-rose.si	Crunchbase Predictive Maintenance
IS-Predict	http://www.ispredict.com/	Hannover Industrie Messe 2018
It-RSC	https://it-rsc.de/	Hannover Industrie Messe 2018
IXON	https://www.ixon.cloud/de	Hannover Industrie Messe 2018
Keysight Technologies	https://www.keysight.com/de/de/home.html	Website List
Kittiwake Developments	http://www.kittiwake.com	Crunchbase Condition Monitoring
Konux	https://www.konux.com/de/	Website List
Koola	http://www.koola.io	Crunchbase Predictive Maintenance
Lufthansa Industry Solutions	https://www.lufthansa-industry-solutions.com/de-en/	Hannover Industrie Messe 2018
MachineSense	https://machinesense.com/	Crunchbase Predictive Maintenance
Materna	https://www.materna.de/	Hannover Industrie Messe 2018
MB connenct line	https://www.mbconnectline.com/	Hannover Industrie Messe 2018
Mech Mine	https://www.mechmine.com/en/	Hannover Industrie Messe 2018
Mera AS	http://www.mera.no	Crunchbase Condition Monitoring
Monixo	http://www.monixo.com	Hannover Industrie Messe 2018

Company	Website	Source
MPEC Technology	http://www.mpec.co.uk	Crunchbase Condition Monitoring
National Instruments	http://www.ni.com/de-de/innovations/industrial-machinery/condition-monitoring.html	Website List
NEXCOM	http://www.nexcom.com/	Hannover Industrie Messe 2018
Nokia	https://spacetimeinsight.com/asset-analytics/	Website List
OSIsoft	https://www.osisoft.com/iiot/	Website List
Otonomo	http://www.otonomo.io/	Crunchbase Webpage Search
Perpetuum	http://www.perpetuum.com	Crunchbase Condition Monitoring
Phase3 Technologies	http://www.phase3-tech.com/	Crunchbase Predictive Maintenance
Pitstop	https://www.pitstopconnect.com	Crunchbase Predictive Maintenance
Planray	http://www.planray.com/en/	Hannover Industrie Messe 2018
Precognize	http://www.precog.co	Crunchbase Predictive Maintenance
Predict Systems	http://predictsystems.com	Crunchbase Predictive Maintenance
Profi Engineering Systems AG	https://www.profi-ag.de/	Hannover Industrie Messe 2018
Progress Software	https://www.progress.com/solutions/cognitive-predictive-maintenance	Website List
ProJugaad	http://projugaad.com	Crunchbase Predictive Maintenance
PTC	https://www.ptc.com/en/products/iot/thingworx-platform/analyze	Website List
Record Evolution	https://record-evolution.de/	Hannover Industrie Messe 2018
Reliability Solutions	http://reliasol.pl/en/	Crunchbase Predictive Maintenance
Roambee Corporation	http://www.roambee.com	Crunchbase Condition Monitoring
Rockwell Automation	https://ab.rockwellautomation.com/Condition-Monitoring	Website List
ROTH	https://www.roth-gruppe.de/	Hannover Industrie Messe 2018
SALT Solutions	https://www.salt-solutions.de/	Hannover Industrie Messe 2018
Semiotic Labs	http://www.semioticlabs.com	Crunchbase Condition Monitoring
Senseye	http://www.senseye.io/	Hannover Industrie Messe 2018
Sensibridge	http://sensibridge.com/	Crunchbase Predictive Maintenance
SH-Tools	https://www.sh-tools.com/de/	Hannover Industrie Messe 2018
SIEVERS Group	https://www.sievers-group.com/	Hannover Industrie Messe 2018
smaris	https://www.smaris.cz/	Hannover Industrie Messe 2018
Smart Component Technologies	https://smartcomptech.com	Crunchbase Condition Monitoring
Softgate	https://www.soft-gate.de/	Hannover Industrie Messe 2018
Spectro	http://www.spectroinc.com	Crunchbase Condition Monitoring
SWMS Consulting	https://www.swms.de/consulting/	Hannover Industrie Messe 2018
Sycor	https://de.sycor-group.com/	Hannover Industrie Messe 2018
Symmedia	https://www.symmedia.de/	Hannover Industrie Messe 2018
Tech Soft	https://www.techsoft.at/	Hannover Industrie Messe 2018
Tensor Systems Pty Ltd	http://www.tensorsystems.com	Crunchbase Condition Monitoring
Teraki	http://www.teraki.com	Crunchbase Predictive Maintenance
Test Motors	http://www.testmotors.com	Crunchbase Predictive Maintenance
Trebing & Himstedt	https://www.t-h.de/	Hannover Industrie Messe 2018
Ventec Systems	http://www.ventech-systems.com	Crunchbase Condition Monitoring
VIRTENIO	https://www.virtenio.com/de/	Hannover Industrie Messe 2018
Wearcheck	http://www.wearcheck.co.za	Crunchbase Condition Monitoring
Weidmüller	https://www.weidmueller.de/	Hannover Industrie Messe 2018
Wirescan	http://www.wirescan.no	Crunchbase Condition Monitoring

References

Afauh, A., & Tucci, C. L. (2001). *Internet business models and strategies: Text and cases*. New York, USA, *MacGraw-Hill/Irwin*.

Aivaliotis, P., Georgoulias, K., & Chryssolouris, G. (2017). A RUL calculation approach based on physical-based simulation models for predictive maintenance. In *Proceedings of the International Conference on Engineering, Technology and Innovation*, Madeira, Portugal, June 25-28, 2017 (pp. 1243–1246).

Alt, R., & Zimmermann, H. D. (2001). Preface: introduction to special section–business models. *Electronic markets*, 11(1), 3–9.

Araiza, M. L. (2004). A formal framework for predictive maintenance. In *Proceedings of AUTOTESTCON 2004*, San Antonio, Texas, USA, September 20-23, 2004 (pp. 489–495).

Backhaus, K., Erichson, B., Plinke, W., & Weiber, R. (2011). *Multivariate Analysemethoden: Eine anwendungsorientierte Einführung*. Berlin/Heidelberg, Germany, Springer.

Baidya, R., & Ghosh, S. K. (2015). Model for a predictive maintenance system effectiveness using the analytical hierarchy process as analytical tool, *IFAC-PapersOnLine*, 48(3), 1463–1468.

Barbera, F., Schneider, H., & Kelle, P. (1996). A condition based maintenance model with exponential failures and fixed inspection intervals. *Journal of the Operational research Society*, 47(8), 1037–1045.

Borgi, T., Hidri, A., Neef, B., & Naceur, M. S. (2017). Data analytics for predictive maintenance of industrial robots. In *Proceedings of the International Conference on Advanced Systems and Electric Technologies*, Hammamet, Tunisia, January 14-17, 2017 (pp. 412–417).

Brousseau, E., & Pénard, T. (2007). The economics of digital business models: A framework for analyzing the economics of platforms. *Review of Network Economics*, 6(2), 81–114.

Cachada, A., Barbosa, J., Leitño, P., Gcraldcs, C. A., Deusdado, L., Costa, J., ... & Romero, L. (2018). Maintenance 4.0: Intelligent and predictive maintenance system architecture. In *Proceedings of the 23rd International Conference on Emerging Technologies and Factory Automation*, Torino, Italy, September 04-07, 2018 (pp. 139–146).

Chen, M. (2013). Towards smart city: M2M communications with software agent intelligence. *Multimedia Tools and Applications*, 67(1), 167–178.

Chu, C., Proth, J. M., & Wolff, P. (1998). Predictive maintenance: The one-unit replacement model. *International Journal of Production Economics*, 54(3), 285–295.

Daily, J., & Peterson, J. (2017). Predictive maintenance: How big data analysis can improve maintenance. In: Richter K., Walther J. (eds) *Supply Chain Integration Challenges in Commercial Aerospace* (pp. 267–278). Springer, Cham.

Darwanto, D., Hamdani, D., Hariyanto, D. D., & Karyawan, O. H. (2012). Partial discharge analysis for predictive maintenance of generator of geothermal power plant. In *Proceedings of the International Conference on Condition Monitoring and Diagnosis*, Bali, Indonesia, September 23-27, 2012 (pp. 740–743).

Dijkman, R. M., Sprenkels, B., Peeters, T., & Janssen, A. (2015). Business models for the Internet of Things. *International Journal of Information Management*, 35(6), 672–678.

Eickhoff, M., Muntermann, J., & Weinrich, T. (2017). What do FinTechs actually do? A taxonomy of FinTech business models. In *Proceedings of the International Conference on Information Systems*, Seoul, South Korea, December 10-13.

Gerloff, C., & Cleophas, C. (2017). Excavating the Treasure of IoT Data: An Architecture to Empower Rapid Data Analytics for Predictive Maintenance of Connected Vehicles. In *Proceedings of the International Conference on Information Systems*, Seoul, South Korea, December 10-13.

Gimpel, H., Rau, D., & Röglinger, M. (2017). Understanding FinTech start-ups–a taxonomy of consumer-oriented service offerings. *Electronic Markets*, 28(3), 245–264.

Glass, R. L., & Vessey, I. (1995). Contemporary application-domain taxonomies. *IEEE Software*, 12(4), 63–76.

Groba, C., Cech, S., Rosenthal, F., & Gossling, A. (2007). Architecture of a predictive maintenance framework. In *Proceedings of the 6th International Conference on Computer Information Systems and Industrial Management Applications*, Elk, Poland, June, 28-30, 2007 (pp. 59–64).

Hartmann, P. M., Zaki, M., Feldmann, N., & Neely, A. (2016). Capturing value from big data–a taxonomy of data-driven business models used by start-up firms. *International Journal of Operations & Production Management*, 36(10), 1382–1406.

Hinton, G. E., & Salakhutdinov, R. R. (2006). Reducing the dimensionality of data with neural networks. *Science*, 313(5786), 504–507.

Hui, D., Wang, T., Leng, Y., & Zhang, Y. (2008). Research of open condition monitor system based on the Predictive Maintenance. In *Proceedings of the Fourth International Conference on Natural Computation*, Jinan, China, October 18-20, 2008 (Vol. 7, pp. 317–320).

Khazraei, K., & Deuse, J. (2011). A strategic standpoint on maintenance taxonomy. *Journal of Facilities Management*, 9(2), 96–113.

Last, M., Sinaiski, A., & Subramania, H. S. (2010). Predictive maintenance with multi-target classification models. In *Proceedings of the Asian Conference on Intelligent Information and Database Systems*, Hue City, Vietnam, March 24-26, 2010 (pp. 368–377).

Mahadevan, B. (2000). Business models for Internet-based e-commerce: An anatomy. *California management review*, 42(4), 55–69.

Mattes, A., Schöpka, U., Schellenberger, M., Scheibelhofer, P., & Leditzky, G. (2012). Virtual equipment for benchmarking predictive maintenance algorithms. In *Proceedings of the 2012 Winter Simulation Conference*, Berlin, Germany, December 09-12, 2012.

Mustakerov, I., & Borissova, D. (2013). An intelligent approach to optimal predictive maintenance strategy defining. In *Proccedings of the IEEE International Symposium on Innovations in Intelligent Systems and Applications*, Albena, Bulgaria, June 19-21, 2013.

Nickerson, R. C., Varshney, U., & Muntermann, J. (2013). A method for taxonomy development and its application in information systems. *European Journal of Information Systems*, 22(3), 336–359.

Önel, I. Y., Caglar, E., & Duyar, A. (2009). New horizons on predictive maintenance. In *Proceedings of the International Conference on Intelligent Control Systems and Signal Processing*, Istanbul, Turkey, September 21-23, 2009 (pp. 120–125).

Osterwalder, A., Pigneur, Y., & Tucci, C. L. (2005). Clarifying business models: Origins, present, and future of the concept. *Communications of the association for Information Systems*, 16(1), 1–25.

Osterwalder, A., & Pigneur, Y. (2010). *Business model generation: a handbook for visionaries, game changers, and challengers*. John Wiley & Sons.

PricewaterhouseCoopers (2017). Predictive Maintenance 4.0. PricewaterhouseCoopers. Retrieved from https://www.pwc.nl/nl/assets/documents/pwc-predictive-maintenance-4-0.pdf [Accessed September 27, 2018].

Richter, A., Vodanovich, S., Steinhüser, M., & Hannola, L. (2017). IT on the shop floor - Challenges of the digitalization of manufacturing companies. In *Proceedings of the 30th Bled eConference*, Bled, Slovenia, June 18-21, 2017 (pp. 483–500).

Sipos, R., Fradkin, D., Moerchen, F., & Wang, Z. (2014). Log-based predictive maintenance. In *Proceedings of the 20th international conference on knowledge discovery and data mining*, New York, USA, August 24-27, 2014 (pp. 1867–1876).

Sokal, R. R., & Michener, C. D. (1958). A statistical method for evaluating systematic relationships. *University of Kansas Bulletin*, 38(2), 1409–1438.

Spendla, L., Kebisek, M., Tanuska, P., & Hrcka, L. (2017). Concept of predictive maintenance of production systems in accordance with industry 4.0. In *Proceedings of the 15th International Symposium on Applied Machine Intelligence and Informatics*, Herl'any, Slovakia, January 26-28, 2017 (pp. 405–410).

Susto, G. A., Beghi, A., & De Luca, C. (2012). A predictive maintenance system for epitaxy processes based on filtering and prediction techniques. *IEEE Transactions on Semiconductor Manufacturing*, 25(4), 638–649.

Susto, G. A., Schirru, A., Pampuri, S., Pagano, D., McLoone, S., & Beghi, A. (2013). A predictive maintenance system for integral type faults based on support vector machines: An application to ion implantation. In *Proceedings of the IEEE International Conference on Automation Science and Engineering*, Madison, Wisconsin, USA, August 17-20, 2013 (pp.195–200).

Täuscher, K., & Laudien, S. M. (2018). Understanding platform business models: A mixed methods study of marketplaces. *European Management Journal*, 36(3), 319–329.

Turber, S., Vom Brocke, J., Gassmann, O., & Fleisch, E. (2014). Designing business models in the era of internet of things. In *Proceedings of the International Conference on Design Science Research in Information Systems*, Miami, Florida, USA, May 22-24, 2014 (pp. 17–31).

Wang, N., Sun, S., Si, S., & Li, J. (2009). Research of predictive maintenance for deteriorating system based on semi-markov process. In *Proceedings of the 16th International Conference on Industrial Engineering and Engineering Management*, Beijing, China, October 21-23, 2009 (pp.899–903).

Wang, J., Zhang, L., Duan, L., & Gao, R. X. (2017). A new paradigm of cloud-based predictive maintenance for intelligent manufacturing. *Journal of Intelligent Manufacturing*, 28(5), 1125–1137.

E Einflüsse der Digitalisierung auf Qualitätsmanagement (DE)

Appendix E

Einflüsse der Digitalisierung auf das Qualitätsmanagement und die Notwendigkeit einer integrierten Betrachtungsweise anhand eines Referenzmodells

Leonie Jürgens, Daniel Olivotti and Michael H. Breitner

Citation: Jürgens, Leonie; Olivotti, Daniel; Breitner, Michael H. (2019). “Einflüsse der Digitalisierung auf das Qualitätsmanagement und die Notwendigkeit einer integrierten Betrachtungsweise anhand eines Referenzmodells”. In: IWI Discussion Paper Series (#89). ISSN: 1612-3646.

Abstract:
In the industrial sector quality management is an important cross-company functionality. Not only increasing or changing value networks but also digitalization has an impact on quality management. More and more “things” get connected and a comprehensive quality management is required. The following paper aims in using key aspects of the digital twin to elaborate critical success factors and a reference model.

Keywords: Digitalization, Quality management, Reference architecture

F A Smart Services Enabling Information Architecture

Appendix F

Towards a Smart Services Enabling Information Architecture for Installed Base Management in Manufacturing

Sonja Dreyer, Daniel Olivotti, Benedikt Lebek and Michael H. Breitner

Citation: Dreyer, Sonja; Olivotti, Daniel; Lebek, Benedikt; Breitner, Michael H. (2017). "Towards a Smart Services Enabling Information Architecture for Installed Base Management in Manufacturing". In: Proceedings of the 13th International Conference on Wirtschaftsinformatik. St. Gallen, Switzerland, February 12-15; 2017. Ed. by J. M. Leimeister; W. Brenner, pp. 31–45.

URL: `https://aisel.aisnet.org/wi2017/track01/paper/3/`

Abstract:
In the manufacturing industry the provision of smart services is an opportunity to gain a competitive advantage. As there are high demands on machine availability, smart services in the field of installed base management are important. Through integrating condition monitoring data with installed base data a digital twin of the installed base can be created. This enables comprehensive analyses and the provision of individualized smart services. But this requires to structure and standardize the data. Following the action design research (ADR) approach, in this article design principles of an information architecture are developed. The architecture is evaluated and improved in the context of an international engineering and manufacturing company. A test run with real machine data shows the applicability in practice.

Keywords: Digital twin, Information architecture, Installed base management, Smart services, Product-Service-Systems

G An integrated installed base management system

Appendix G

Creating the foundation for digital twins in the manufacturing industry: an integrated installed base management system

Daniel Olivotti, Sonja Dreyer, Benedikt Lebek and Michael H. Breitner

Citation: Olivotti, Daniel; Dreyer, Sonja; Lebek, Benedikt; Breitner, Michael H. (2018). "Creating the foundation for digital twins in the manufacturing industry: an integrated installed base management system". In: Information Systems and e-Business Management 17 (1), pp. 89–116.

DOI: 10.1007/s10257-018-0376-0

Abstract:
Services play an important role in the manufacturing industry. A shift in emphasis from selling physical products to offering product–service systems is perceived. Detailed knowledge of machines, components and subcomponents in whole plants must be provided. Installed base management contributes to this and enables services in manufacturing to maintain high machine availability and reduce downtimes. Installed base management assists in data structuring and management. By combining installed base data with sensor data, a digital twin of the installed base results. Following the action design research approach, an integrated installed base management system for manufacturing is presented and implemented in practice. An engineering and manufacturing company is involved in the research process and ensures practical relevance. Requirements are not only deduced from the literature but also identified in focus group discussions. A detailed test run with real data is performed for evaluation purpose using a demonstration machine. To enable a generalization, design principles for the development and implementation of such an integrated installed base management system are created.

Keywords: Installed base management, Integrated installed base management system, Digital twin, Action design research (ADR)

H Modeling Framework for Product-Service Systems

Appendix H

Modeling Framework for Integrated, Model-based Development of Product-Service Systems

Hristo Apostolov, Matthias Fischer, Daniel Olivotti, Sonja Dreyer, Michael H. Breitner and Martin Eigner

Citation: Apostolov, Hristo; Fischer, Matthias; Olivotti, Daniel; Dreyer, Sonja; Breitner, Michael H.; Eigner, Martin (2018). “Modeling Framework for Integrated, Model-based Development of Product-Service Systems”. In: Procedia CIRP 73, pp. 9–14.

DOI: 10.1016/j.procir.2018.03.307

Abstract:
Product-service systems (PSS) are seen as the 21st-century solution for direct delivery of value to customers under the requirements of high availability, quality, and reduced risks. With mutual benefits for customers, manufacturers, service providers and often the environment, PSS represent a promising approach to sustainable development. This paper addresses the integrated development of product-service systems consisting of physical products/systems and services and proposes an integrated modeling framework that utilizes the Systems Modeling Language. A use case from Lenze, a German automation company, demonstrates the applicability of the integrated modeling framework in practice.

Keywords: Product-Service-System, Model-Based Systems Engineering, Service engineering, Systems Modeling Language (SysML)

I A smart service literature review

Appendix I

Focusing the customer through smart services: a literature review

Sonja Dreyer, Daniel Olivotti, Benedikt Lebek and Michael H. Breitner

Citation: Dreyer, Sonja; Olivotti, Daniel; Lebek, Benedikt; Breitner, Michael H. (2019). "Focusing the customer through smart services: a literature review". In: Electronic Markets 29 (1), pp. 55–78.

DOI: 10.1007/s12525-019-00328-z

Abstract:
Smart services serve customers and their individual, continuously changing needs; information and communications technology enables such services. The interactions between customers and service providers form the basis for co-created value. A growing interest in smart services has been reported in the literature in recent years. However, a categorization of the literature and relevant research fields is still missing. This article presents a structured literature search in which 109 relevant publications were identified. The publications are clustered in 13 topics and across five phases of the lifecycle of a smart service. The status quo is analyzed, and a heat map is created that graphically shows the research intensity in various dimensions. The results show that there is diverse knowledge related to the various topics associated with smart services. One finding suggests that economic aspects such as new business models or pricing strategies are rarely considered in the literature. Additionally, the customer plays a minor role in IS publications. Machine learning and knowledge management are identified as promising fields that should be the focus of further research and practical applications. Concrete ideas for future research are presented and discussed and will contribute to academic knowledge. Addressing the identified research gaps can help practitioners successfully provide smart services.

Keywords: Smart services, Value co-creation, Literature review, Status quo analysis, Future research agenda

J Knowledge Management Systems' Design Principles for Smart Services

Appendix J

Knowledge Management Systems' Design Principles for Smart Services

Sonja Dreyer, Daniel Olivotti and Michael H. Breitner

Was submitted

Abstract:
Smart services became increasingly important in the last years. Organizations noticed that the provision of smart services in addition to their current portfolio is advantageous. Smart services are individual services that are adapted to the customer's requirements and the current context, resulting in strong relationships between customer and smart service provider. To be able to react immediately to changing conditions, various and frequently changing data are collected and analyzed. Knowledge is necessary to turn data into valuable information. Smart services are usually provided in value networks. Different participants of a value network have different, domain-specific knowledge. Additionally, knowledge is generated during the operation phase of smart services. A knowledge management system adapted to the requirements of the provided smart services is necessary to consolidate, maintain and provide knowledge. Until now, little research has been done in the field of knowledge management for smart services. Although some publications emphasize the importance of knowledge in connection with smart services, an overview how diverse knowledge management for smart services can be designed, is missing. Literature focusing smart services is analyzed and directly or indirectly named requirements for knowledge management are extracted. Smart services are highly complex which is why requirements differ; there is not the only one best solution for the design of a knowledge management system. Therefore, a model in form of a cube is developed. The knowledge management cube model shows different possibilities of how to design knowledge management for smart services.

Keywords: Smart service, Individual service, Knowledge management, Knowledge management system

Knowledge Management Systems' Design Principles for Smart Services

Abstract:

Smart services became increasingly important in the last years. The provision of smart services in addition to current product portfolios is advantageous. Smart services are individual services adapted to customers' requirements resulting in strong relationships between customers and smart services' providers. To react immediately to changing requirements, various and frequently changing data must be collected and analyzed. Specific knowledge is necessary to turn data into valuable information. Smart services are usually provided in value networks and participants have different, domain-specific knowledge. Additionally, knowledge is generated during the operation of smart services. A knowledge management system (KMS) adapted to requirements of provided smart services is necessary to aggregate, maintain and provide knowledge. Little research is available in the field of KMS for smart services (KMSSS). Although some publications emphasize the importance of knowledge for smart services, an overview how tailored KMSSS can be designed is missing. A comprehensive literature review is carried out and directly or indirectly named requirements for knowledge management are extracted. Smart services are highly complex which is why requirements differ: there is not the only one best solution for the design of a KMSSS. Therefore, we develop a cubic reference model and show a tailored KMSSS in practice.

Keywords:

Smart services, Knowledge management systems (KMS), Customer-centric design principles, Reference model

1 Introduction

Offering services in addition to products or offering services that make buying products obsolete, becomes more and more important (Oliva and Kallenberg 2003; Böhmann et al. 2018). Smart services arise because they use opportunities resulting from digitalization and the Internet of Things (Georgakopoulos and Jayaraman 2016). Smart services are individual services that can adapt themselves to the environment (Beverungen et al. 2017). To be able to offer smart services efficiently, a comprehensive and reliable knowledge management is required (Zhang et al. 2012; Al Nuaimi et al. 2015,), including, e.g., mathematical models and rules. Knowledge management describes the handling of all kind of knowledge (Fahey 2001).

Knowledge management is especially important for smart services because environment and requirements related to smart services can change immediately (Oh et al. 2010). It is necessary to react to changing conditions because this distinguishes smart services from other types of services. Smart services can only be provided successfully if information and knowledge are available where and when required (Beverungen et al. 2017). For interpreting sensor data, knowledge is necessary. A knowledge management system (KMS) is a prerequisite to be able to react individually (Li et al. 2015). Depending on the specific smart services the designs of KMS for smart services (KMSSS) differ.

In a connected world, knowledge management is not anymore limited to a department or a company. A whole value network must be included (Abbate et al. 2015; Delfanti et al. 2015). As the research field of smart services is a relatively new one, there is only a little number of publications focusing on tailored KMSSS. Although some authors emphasize the importance of a reliable knowledge management for providing smart services successfully (e.g., Wang et al. 2011), in most publications they do not focus on it. An overview showing what are characteristics and key capabilities of KMSSS is still missing. But, it contributes to a better understanding what makes smart services successful. A systematic approach investigates how tailored KMSSS can be designed. Smart services are diverse, and this is reflected in diverse, tailored knowledge management approaches. Therefore, we formulated the following research question:

RQ: How can customer-centric knowledge management systems for smart services be designed?

To answer our research question, we conduct a comprehensive literature search in the field of smart services, using a Webster and Watson (2002) oriented approach. As smart services are knowledge-intensive services (Chu and Lin 2011) all publications contained requirements regarding customer-centric knowledge management processes and information systems (IS) for smart services. These requirements were either formulated explicitly or implicitly. We analyzed the requirements in form of characteristics, functional capabilities, and technical conditions. We developed a reference model that illustrates the diversity of tailored KMSSS designs and design principles.

The paper is structured as follows: In the second section smart services and KMS are outlined and combined subsequently to KMSSS. The third section explains our research design. Our KMSSS reference model is developed afterwards, showing the diversity of design possibilities. It is followed by a discussion of our results, analyzing the influence of knowledge management on organizations and vice versa, too. Design principles are also presented. The paper ends with our limitations, our conclusions and our outlook in sections six and seven.

2 Literature Review

Smart services enable new business opportunities and revenue channels. Gavrilova and Kokoulina (2015) state out that the aim of smart services is the co-creation of value by consumers and smart services' providers. Thus, smart services are based on collaboration and customer interaction to gain value and are not only just consumed by customers (Baldoni et al. 2010; Demirkan et al. 2015; Beverungen et al. 2018). Machine intelligence and connected IS are required to enable value co-creation. Information and communication technology (ICT) must be used for smart services to be able to react to customer requirements and an individual customer context (Calza et al. 2015). Analyses using machine intelligence are based on data collection in real-time (Allmendinger and Lombreglia 2005). Several data sources and social contexts can be included for a single service (Lee et al. 2012; Alahmadi and Qureshi 2015). Then, data analysis tools and mechanisms are used to process this information to gain knowledge that can be used by smart services (Kynsiletho and Olsson 2012; Stoehr et al. 2018). Individual customer requirements are addressed, and quality of processes is improved through smart services (Massink et al. 2010). These aspects are summarized in the characteristics presented by Dreyer et al. (2019):

- Individual and highly dynamic service solutions
- Use of ICT and field intelligence
- (Real-time) analyses of technology, environment and social context data
- Value co-creation between customers and providers

Knowledge management is based on the identification and leveraging of knowledge in organizations to compete in the market (von Krogh 1998; Liu et al. 2017). It is embedded in KMS that "support creation, transfer, and application of knowledge in organizations" (Alavi and Leidner 2001, p. 107). This applies especially to knowledge-intensive processes (Massey et al. 2002; Sarnikar and Deokar 2017). Davenport and Prusak (1998) see three goals of knowledge management in organizations: visibility of knowledge, encourage knowledge sharing, and build an infrastructure for people to share knowledge. According to Fahey (2001) there are mainly three processes that are continuously repeated: new knowledge is discovered or created, the knowledge is shared between people and within the organization and is used then in daily work and for decision making. We see knowledge management in accordance with Fahey (2001) and Davenport and Prusak (1998) as a process from gaining or discovering knowledge, sharing knowledge to people and organizations and the facilitation of the usage of knowledge through organizational and technological mechanisms.

Knowledge is the basis to enable value co-creation between smart services' providers and customers in value networks (Payne et al. 2008; Bagheri et al. 2016). Knowledge management is inevitable because not only static, structured data is used to describe a customer's environment, but also highly dynamic and individual data (Lee et al. 2012). Knowledge management must be flexible and able to adapt itself to the context (Theocharis and Tsihrintzis 2013). Chatterjee and Armentano (2015) describe how to obtain intelligence from data. For smart services, an extension from an internal company knowledge management to a value network knowledge management must be performed (Bagheri et al. 2016; Stoehr et al. 2018). Therefore, an KMSSS architecture must be developed (Badii et al. 2017). A challenge is that knowledge integration from different sources must be ensured (Wang et al. 2011). To the best of our knowledge, there is no reference model existing so far connecting the design of KMS to smart services. This approach contributes to a better understanding of smart services both theoretically and in practice.

3 Research Design

Our research goals are to identify implicitly and explicitly named requirements for tailored KMSSS and to develop design principles and a KMSSS reference model. Therefore, we analyzed literature that deals with smart services, regardless of whether knowledge management is explicitly named. The requirements were extracted through a comprehensive analysis of the literature. In our research, these requirements are presented. Besides requirements that arise for knowledge management in general, there are also requirements specific for smart services. We developed a KMSSS reference model: the cubic model shows the variety of tailored KMSSS designs.

A comprehensive literature search was conducted to identify relevant literature in the field of smart services. It was oriented on the structured approach presented by Webster and Watson (2002). To ensure a rigorous literature search, both reliability and validity have to be guaranteed (Vom Brocke et al. 2009). Reliability refers to the precision of scientific research (Vom Brocke et al. 2009). In the context of our research, we documented the search process by describing the procedure including the used databases and search terms. Inclusion and exclusion criteria were specified to make the results of the literature search transparent. Validity was understood as the degree of accuracy. Referring to a literature search, it was the degree to which all relevant publications were found. We ensured validity by conducting a literature search in eight different databases: ACM, AISeL, Emerald Insight, IEEEXplore, InformsOnline, JSTOR, Science Direct, and SpringerLink. Additionally, we did not only search for articles containing the term "smart service". Therefore, we were able to identify articles that consider services that are smart according to our understanding, but that do not use the term "smart service". We predefined the three following search terms that were used for the search in the different databases: "smart service" OR "smart services", "digital service" OR "digital services", "electronic service" OR "electronic services" OR "e-service" OR "e-services". Moreover, both forward and backward searches were conducted.

To receive search results that focus on smart services, only the title and the abstract were considered where it was possible. After generating the search results, inclusion and exclusion criteria were defined to filter the results. First, all articles that were not written in English were excluded. We assumed that researchers write research articles of high quality in English to reach a global community. Second, non-academic literature was excluded, and not peer-reviewed papers were filtered out.

Our goal was to extract most of the relevant publications that deal with smart services. The characteristics presented in Chapter 2 were used to identify which articles of the remaining search results deal with smart services in our view. This resulted in a large reduction of possibly relevant articles because the second and third search terms, i.e. digital service and electronic service, often are not used as synonyms for smart services.

Both forward and backward searches were conducted as recommended by Webster and Watson (2002). In the forward search it was checked where the publications are cited. Within the backward search the citations of the relevant publications were reviewed to identify further relevant articles. Finally, 157 articles were considered in the following (a complete list of all articles can be found in the appendix).

All articles that were identified to be relevant were comprehensively reviewed. The whole texts were examined regarding requirements for knowledge management. Although knowledge or knowledge management often is not explicitly addressed, requirements are named implicitly when describing a service and its application. For example, it is emphasised that human-generated knowledge must be considered for decisions (Lee et al. 2015).

Characteristics are extracted that are not always applicable in the same way for different smart services, e.g., the necessary reaction speed. All identified aspects were classified in one of the following three categories: characteristics, capabilities, and technical functions. These categories were not predefined but developed during the review process. It turned out that all requirements that were named in the literature can be assigned to exactly one of the three categories. These formed the basis for our KMSSS reference model, developed with orientation on Becker and Delfmann (2007). The reference model shows the diversity of tailored KMSSS designs. The subsequent discussion includes implications for practitioners. Figure 1 summarizes our research design.

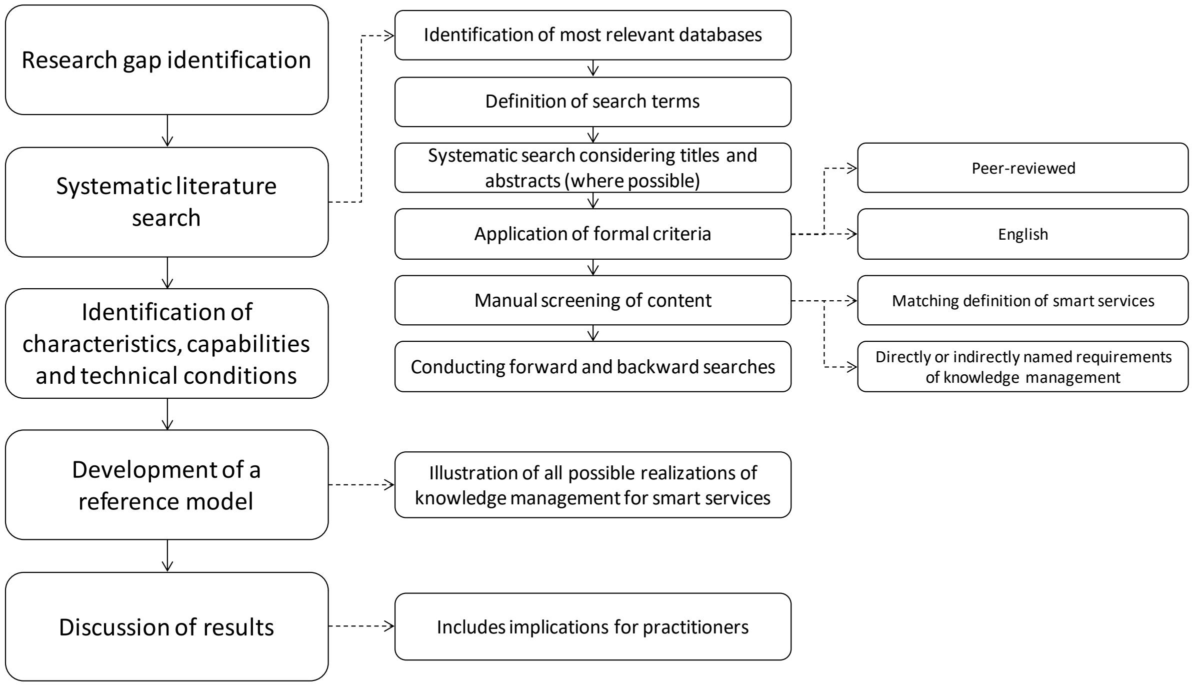


Figure 1: Research design

4 Tailored KMSSS

Although we limit our research to smart services, there is a wide range of diverse KMSSS designs. In the following, characteristics, capabilities and technical conditions extracted from the literature are presented. They are used subsequently to develop a KMSSS reference model, including all designs. A real-world example demonstrates why knowledge management is necessary for smart services.

4.1 Characteristics

When providing smart services, these are not realized by a single company. Usually, a value network is created to be able to provide and operate smart services successfully (Mathes et al. 2009; Tien 2012). As different participants of a value network are involved, KMSSS are complex compared to other applications (Bullinger et al. 2017). Additionally, not only the cross-company use is complex, but also the use within a company. Several different departments are participating with different interests and foci (Saunila et al. 2017). The more participants have access to the KMSSS, the more coordination effort is required (Tianyong et al. 2006).

Many different sources are used to realize a comprehensive and useful knowledge management (Perera et al. 2014; Korzun et al. 2015). One important source is the knowledge in the employees' heads (Barile and Polese 2010). Implementing this knowledge into the KMSSS requires suitable processes (Smirnov et al. 2015). The objective is that not only other employees can use the knowledge, but also machines (He et al. 2012). Depending on the smart services for which the knowledge is used, not only directly entered knowledge forms part of the KMS (Kynsilehto and Olsson 2011). Knowledge that is generated during smart services' operation must be included automatically, too (Mo et al. 2010).

Knowledge management is not static but dynamic (Yachir et al. 2009; Alti et al. 2015). Thus, knowledge is not only implemented once at the beginning. Knowledge management is living, and the content is changing and extended over time (Ren et al. 2014). An open KMSSS design contributes to living and always topical knowledge (Barile and Polese 2010; Anttiroiko et al. 2014). It is important that a certain quality is ensured (Fan et al. 2012; Mihovska et al. 2015). From a smart services' perspective, quality has an influence on the reuse of a service (Zo 2003). In connection with quality, transparency is important for useful knowledge management (Lesjak et al. 2014; Priller et al. 2014). As knowledge can be added and modified by several participants, mechanisms are required to track changes, too.

It is necessary that the knowledge management works efficiently (Yu 2004). For example, the storage of knowledge must be efficient since the amount of knowledge is growing over time. Efficient concepts and strategies must be implemented to store and manage knowledge efficiently (Al Nuaimi et al. 2015). Necessary knowledge must be extracted in a suitable time to be able to react to the current situation (Ciortea et al. 2016). Not only smart services as such are diverse, the contexts also are (Mo et al. 2010; Kwak et al. 2014). Smart services are characterized by the ability to be context-sensitive (Li et al. 2015; Seeliger et al. 2015; Wutzler et al. 2017). Technical, social and environmental information is considered to adapt smart services continually (Lee et al. 2012; Alahmadi and Qureshi 2015). It must be possible to use the same KMSSS in different contexts (Weijie et al. 2012).

Knowledge management enables access for different participants of a value network to the same knowledge base (Delfanti et al. 2015; Hussein et al. 2017). As smart services are characterized by value co-creation (Gavrilova and Kokoulina 2015), not only participants involved in the provision of smart services form part of the value network; smart services' customers also participate actively (Mikusz 2017). Thereby, information asymmetries between providers and customers are compensated (Dawid et al. 2016). But a challenge is that participants of a value network describe knowledge from a specific view (De Oliveira and Silva 2015). However, the knowledge should be useful for different participants and not only for the one who implemented it. This challenge also arises when modifying existing knowledge. Taking an algorithm to improve energy efficiency as an example (Byun and Park 2011), it must not be modified in a way that it is only more customer-centric for a single application, but less useful for all other ones. Nevertheless, it does not mean that domain-specific knowledge must not be part of the knowledge included in the KMSSS (Berna-Martinez et al. 2006). To sum up, the following KMSSS characteristics were identified (Table 1):

Table 1: Identified characteristics of KMS

Characteristic	**General requirement**	**Smart service's requirement**
Usage across departments	✓	✓
Usage in value networks		✓
Input sources are diverse	✓	✓
Usage by both people and machines		✓
Dynamic	✓	✓
Transparent	✓	✓
Applied in different contexts		✓
Standardized knowledge	✓	✓

4.2 Capabilities

Apart from characteristics of knowledge management there are also functional capabilities that must be ensured. Knowledge management is characterized by a collection of knowledge. Many types of knowledge must be integrable (Li et al. 2015; Badii et al. 2017). Knowledge does not only include information in form of texts but also, e.g., algorithms, rules, methods and optimization models (e.g., Maleshkova et al. 2016). Existing knowledge must be combinable with new knowledge (Kim et al. 2015) to continually improve and expand the knowledge base. The mentioned new knowledge can be entered directly (Westwood and Cazier 2016), e.g., by employees, or extracted automatically using various techniques.

Smart services often operate in real-time (Tien 2012; Mukudu et al. 2016; Huang 2017) which is why the KMSSS must work in a performant way (Mihovska et al. 2015). As many different types of smart services are possible or already existing (Delfanti et al. 2015), the dynamics of knowledge management differ. This concerns the rate of change of knowledge. Additionally, the necessary deployment speed varies. Usually, the higher the speed, the higher costs occur. Therefore, it must be determined which speeds are required for respective smart services and connected customers (Kwak et al. 2014).

Classifications of knowledge contribute to realize efficiency (Byun and Park 2011; Chatterjee and Armentano 2015). Depending on the provided smart services, the most suitable classification changes (Alti et al. 2015). For example, it is possible to separate mathematical models from further knowledge. The idea is that knowledge can be provided faster when only the respective class of knowledge is considered. The KMSSS should be able to identify redundant information (Alti et al. 2015). This provides several advantages. On the one hand, possible inconsistencies are avoided and storage space is saved. On the other hand, the knowledge management works more efficiently. The KMSSS must be able to check carefully if there are duplicates (Wang et al. 2011).

Smart services are context-aware services (Mo et al. 2010). Depending on the respective context, e.g., customer-centric recommendations from the KMSSS differ (Yachir et al. 2009; Wünderlich et al. 2012). The challenge is that contexts can be diverse and each context is individual (Mikusz 2017). To meet this challenge, the KMSSS has to generalize context information to be able to react adequately. An important function of a KMSSS is that it can build relationships between different information and knowledge (Barile and Polese 2010; Chu and Lin 2011). Therefore, new knowledge can be generated without new input (Al Nuaimi et al. 2015). But it must also be possible that knowledge is adapted manually (Westwood and Cazier 2016). A KMSSS must support both ways to generate new knowledge and thereby to improve the connected smart services. Protocols that register all activities in the KMSSS contribute to transparency (Chu and Lin 2011). In this case, security and privacy concerns are important challenges of KMS (Strüker and Kerschbaum 2012; Ye and Qian 2017). Not all knowledge that is stored in the KMSSS should be available for all participants. Therefore, role-based authentication is necessary. Only knowledge should be accessible that is relevant for the respective user. Due to this, a flood of information and knowledge is avoided, too. Additionally, the more users have access and modification rights for a specific area of a KMSSS, the higher is the risk of falsification of knowledge.

The KMSSS must be able to output adequate knowledge in a structured way (Chu and Lin 2011). This refers to the amount of knowledge and the depth. For example, when smart services are implemented for the first time at a customer's location, the main functionalities concerning the respective smart services have to be ensured. In the later operation phase, more specific knowledge is required to adjust smart services and their contributions efficiently. As the required knowledge depth and diversity is not entered directly, functions are necessary to identify it. Knowledge that was used once must be accessible for future use (Martin et al. 2014). Therefore, knowledge management must be well structured (Wang et al. 2011). As the knowledge must be readable and usable by all participants of the value network, their devices and connected IS, standardization is necessary (Ma et al. 2010).

The collected and processed knowledge is not only used for display purposes, but in the smart services' context it is used within processes (He et al. 2012). For example, knowledge is used for decision support (Tien 2012; Gretzel et al. 2015). In order to make the best decision, a structured and reliable knowledge management is required that works efficiently. This refers to both proactive activities and requests. It implies that a KMSSS triggers with or without manual intervention (Jerald et al. 2016). Table 2 sums up the identified KMSSS capabilities.

Table 2: Identified functional capabilities of KMS

Functional capability	General requirement	Smart service's requirement
Integrability of many types of knowledge	✓	✓
Combining knowledge	✓	✓
Generating knowledge automatically		✓
Reaction in real-time		✓
Efficient storage	✓	✓
Efficient management	✓	✓
Avoiding redundant knowledge	✓	✓
Generalizing context information		✓
Meeting security and privacy concerns	✓	✓
Situation-sensitive output		✓
Standardizing knowledge	✓	✓
Reliability and robustness	✓	✓

4.3 Technical Conditions

A KMSSS is not isolated, but interacts with other tools and applications (Allmendinger and Lombreglia 2005). For example, tools for decision support must be considered and implemented in the network for smart services (Tien 2012; Gretzel et al. 2015) and interfaces must be provided (Bedogni et al. 2013). Not only technical interfaces between devices and other tools must be considered, but also a user interface must exist (Baldoni et al. 2010). Through a user interface, employees are able to extend the knowledge base and make individual knowledge accessible for other employees and participants of the value network as well as usable for devices and other IS.

Knowledge management has to be integrated in the technical smart services' concept and strategy. This can be realized due to integrating the KMS in a middleware (Wutzler et al. 2017). This implies that different sources are not directly connected. Data and information from different sources can be synchronized (Allmendinger and Lombreglia 2005). There are multiple possibilities to implement a middleware (Pereira et al. 2018). Database management systems need to be used to combine knowledge from different databases and to establish connections to different IS. Different types of databases exist for specific knowledge, e.g., multimedia databases (Alavi and Leidner 2001). Company information can also be stored on Internet or intranet sites to be easily accessible (Alavi and Leidner 2001). Depending on structure and amount of knowledge, memory and process speeds are factors that must be considered. Based on these database technologies, methods such as error analysis, machine learning and knowledge discovery can be realized (Liao 2003).

Employees must have the possibility to maintain the knowledge base manually (Westwood and Cazier 2016). Concepts and strategies how to realize this, e.g., generating reports of all activities or integrating feedback functions, must be implemented to ensure transparency (Chu and Lin 2011; Li et al. 2015). Not only concepts and strategies for role-based authentication have to be developed, but these must also be implemented as part of the KMSSS (Wutzler et al. 2017). For one thing, the KMSSS must be secure. Otherwise, access must be simple to be able to react quickly (Mathes et al. 2009; Holgado and Macchi 2014). A summary of the identified KMSSS technical conditions can be found in Table 3.

Table 3: Identified technical conditions of KMS

Technical condition	General requirement	Smart service's requirement
Interfaces to other tools and IS		✓
User interface	✓	✓
Integrability in a middleware		✓
Role-based authentication		✓

4.4 Reference Model

The analyzed requirements that are not the same for diverse types of smart services are taken to describe a KMSSS reference model. It displays diverse designs of tailored KMSSS. It is realized with a cube and has three dimensions: input/output, structure and reliability (Figure 2).

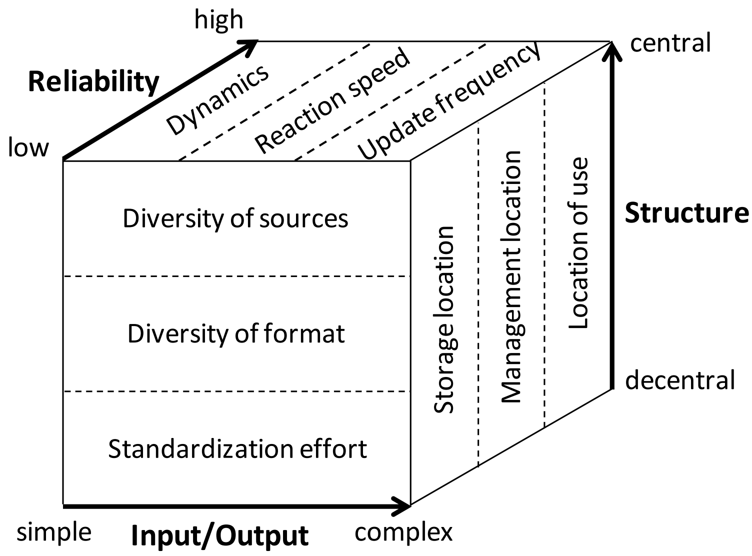


Figure 2: KMSSS reference model

The first dimension concerns the input as well as the output. Knowledge management can only exist with input from which knowledge is generated (Al Nuaimi et al. 2015). The knowledge comes from diverse sources (Delfanti et al. 2015). The more sources are considered the more complex is the KMSSS. Thereby, many different types of knowledge are possible (Cellary 2013). Relatively simple forms are text information. But there are also many different further types of knowledge possible, such as mathematical models or algorithms (Keskin and Kennedy 2015). The input can be structured or unstructured. Additionally, standardization was already discussed in the context of knowledge for smart services (e.g., Berna-Martinez et al. 2006). Depending on the smart services it can be easy to standardize the necessary knowledge. This supports fast searches and simplifies the storage and processing of knowledge. Furthermore, it is readable by different devices and usable by several tools (Ciortea et al. 2016). It is also possible that standardization requires huge effort (Tianyong et al. 2006). The mentioned input is not necessarily direct input but can also be indirect, i.e., new knowledge is generated from operating smart services (Cellary 2013). Similar to the input, the forms of output are diverse and vary from relatively simple to complex. This depends on the smart services for which the KMSSS serves.

Structure is the second dimension of the reference model. It includes diverse aspects regarding local conditions. The first one is local or public knowledge storage (Fan et al. 2016). Implementations between these two are also possible. As different participants of a value network use the same KMSSS, the location regarding the storage is important (Ferretti and Angelo 2016). Usually, there is knowledge that is relevant for all or most participants (Töytäri et al. 2017), e.g., the topology of a production machine when smart services are offered for failure detection. This knowledge can be stored globally. But there is also knowledge that is specific or sensible. For this type of knowledge, it is recommended to store it locally. Depending on the provided smart services a storage concept and strategy must be developed. The same applies for the management. It is possible to have a KMSSS that is managed centrally for the different participants (Ferretti and Angelo 2016). But it is also possible that the participants maintain their knowledge on their own. If the knowledge is stored and managed centrally, it is useful to also use the knowledge centrally. For example, this means that models or decision support systems (DSS) are executed in a cloud and not on a local server. Security and performance issues have to be considered when designing the structure of the KMSSS.

Reliability is the third dimension that is considered within the cube. Smart services are dynamic (Batubara 2015). As knowledge management supports or even enables smart services, it must be equally dynamic. Knowledge management only works reliably when this is ensured. Coming from the provided smart service, the speed in which action is required differs. Partially, very quick reactions are necessary (Holgado and Macchi 2014), e.g., to avoid a machine downtime. In other cases, e.g., process optimization, the high speed is not necessary. Depending on the type of knowledge, update cycles differ (Strüker and Kerschbaum 2012). In some cases it is inevitable to update the knowledge immediately. In other cases it is sufficient to do so in determined periods. Holding the reliability of knowledge management as high as possible seems to be the best solution at first sight. But it must be considered that high costs are related to that.

Table 4: Three dimensions and aspects of the KMSSS reference model

Dimension	Aspect	Description
Input/output	Diversity of sources	The more sources are considered to gain knowledge, the more complex is the KMSSS.
	Diversity of format	Knowledge has many different formats and can be unstructured or structured.
	Standardization effort	Effort to standardize knowledge is related to the complexity of the input and output as well as the related smart services.
Structure	Storage location	Knowledge can be stored locally at a server of a value network participant or centrally, e.g., in a cloud.
	Management location	Responsibility for the KMSSS can be concentrated or distributed over the value network participants.
	Location of use	Methods, models or further knowledge can be used centrally, e.g., in a cloud, or copied and stored locally for further use.
Reliability	Dynamics	The more dynamic smart services are the higher are the requirements for the KMSSS dynamics.
	Reaction speed	Smart services can make real-time reactions necessary which is why the KMSSS often must react quickly.
	Update frequency	The higher the demands regarding reliability of the KMSSS are the higher is the update frequency.

Each point of the cube depicted in the developed reference model is one design of a tailored KMSSS. Depending on the provided smart services the most suitable design of a tailored KMSSS differs. Table 4 summarizes the aspects that are considered when looking at the dimensions of the cubic reference model.

4.5 Applicability Check

The following real-world example demonstrates how a KMSSS can be used in industrial companies to improve processes, offer services and to gain value. We focus on a value network consisting of component supplier, machine builder and machine operator in the industrial sector. Predictive maintenance as a smart service helps machine operators to keep machines' availability high and to reduce the risk of machine breakdowns.

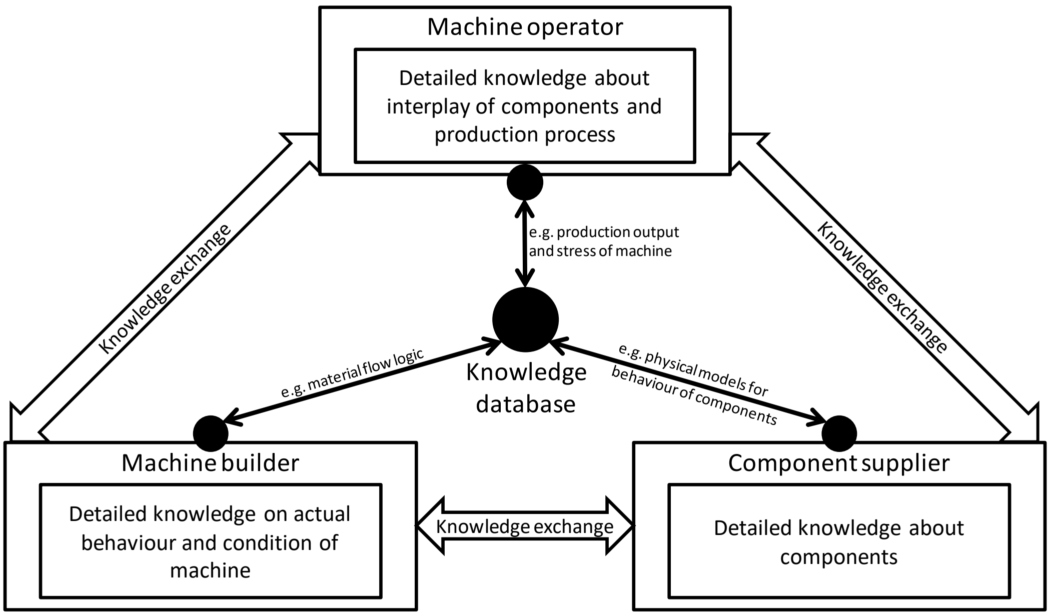


Figure 3: Exemplary knowledge flow in a value network for predictive maintenance activities

An overview about the real-world example for the presented value network can be found in Figure 3. Each participant of the value network has the best knowledge about its own components, machines or processes. With the help of a tailored KMSSS this knowledge can be combined and additional knowledge can be generated. All partners benefit from knowledge exchange and are therefore willing to share their domain knowledge. During machine operation, sensor data provide the current state of a machine or production process. Data analysis of these sensor data must be combined with individual knowledge of the specific machine or the current production process. Knowledge about the machine is provided by the machine builders, having detailed knowledge about the interplay of components, machine functions and machine structure. When a component problem is identified, machine operators and machine builders presumably have no detailed knowledge about the individual component. The component supplier has better possibilities to detect anomalies or failures when knowledge about the production processes or individual applications of the machine is provided. As knowledge used for the explained smart service often is a company secret, a KMSSS structure primarily local is useful. Another argument for a decentralized structure is that knowledge is very specific which is why it can only be maintained by the participant that provided it. In case an external provider is responsible for maintaining the KMSSS a central structure would be required.

Predictive maintenance raises the question when a machine should be maintained and which spare parts are needed therefore. Prediction models based on the previously described knowledge enable to predict when maintenance must be performed. This maintenance should be performed based on current usage of the machine and not according to fixed maintenance schedules. Production planning requirements must be considered to find the best time frame between probability of breakdown and cost for a machine downtime. The reliability does not necessarily have to be very high for this part of the predictive maintenance service because an adaption in real-time is not required. The maintenance scheduling should be adapted within hours, but an extreme high availability of the KMSSS is not required. If the focus of predictive maintenance is not only to plan maintenance activities but also to avoid failure, reactions within minutes might be necessary. In this case, a high reliability and availability of the KMSSS is required.

Machine builders and component suppliers have various customers. Comparing machine operations of different customers shows anomalies of specific customers. Also, the comparison of different production plants shows anomalies. With the help of this, knowledge specific actions can be taken, and machine availability can be ensured. It must be guaranteed hereby that data is anonymized and not shared with unauthorized companies. Input and output are more complex than in the case of smart services where common knowledge is used and adapted.

5 Results, Discussion, Implications and Recommendations

In the literature, knowledge is emphasized to be very important for successful smart services (Wang et al. 2011). A reliable knowledge management enables to continually improve provided smart services. As a characteristic of smart services is that they are individually and continually adapted, knowledge is necessary (Li et al. 2015). For example, sensor data as such are not valuable. Interpreting this data and transforming it into information generates value. A tailored KMSSS is not a rigid IS, but underlies a continual transformation. New knowledge is added, existing knowledge is substantiated, or redundant knowledge is consolidated. Although it is possible to automate these processes partially, it is necessary that the people that form part of the value network of smart services also form an active part of the tailored KMSSS. Often, knowledge only exists in the heads of the employees. To be able to provide smart services on the long term, it is necessary that knowledge is stored and subsequently provided systematically. Both other participants of the value network and machines need to be able to read and use the knowledge. Standardization helps to achieve this. But tailored KMSSS must be flexible to be customer-centric. Therefore, a balance must be found between standardization and flexibility. This is reflected in the input/output dimension of the developed reference model. The individual context must be considered to provide adequate output and the KMSSS should be able to react to changing circumstances. Thereby it must be considered that smart services partially require reactions in real-time. A standardized and efficiently working KMSSS is required to enable it.

Participants of the value network are different companies and customers. Not all knowledge in the KMSSS is intended for all participants. It includes internal knowledge such as algorithms or mathematical models. Furthermore, not all knowledge is relevant for all participants. To avoid a flood of data, a suitable concept and a strategy of how to manage data and knowledge streams is inevitable. Interfaces to other IS and tools are advantageous. In this context, security and privacy concerns arise. This does not only affect processes, but also the technical infrastructure. If there is already an infrastructure existing, the KMSSS has to be embedded adequately. This is important for the reliability dimension of the presented reference model. Role-based authentication is helpful for efficient knowledge management. The roles can differ across the participants of the value network, across employees in the same company, and even across employees of the same department. But, role-based authentication is not the only possibility when thinking about controlled access to knowledge. It is also possible not to centrally store the whole knowledge. It is possible that some participants have not only access to a central KMSSS, but also own local ones. This is represented by the structure dimension of the reference model. Depending on the type of knowledge the participant who stores the knowledge can give access to other participants. It can result in a KMSSS that is partially public and partially local. This has effects on the administration. Such a KMSSS cannot be managed centrally, but the various providers of knowledge must maintain their part of the KMSSS. As smart services are not locally based but are provided globally, remote access is inevitable. For example, tunnel services can be implemented. Table 5 presents recommendations for tailored KMSSS design that result from the discussion and considered implications.

Table 5: Recommendations for KMSSS design

Recommendation	**Comment on the application**
Automated knowledge generation	The KMSSS must be a living IS. New knowledge from operating smart services should be integrated automatically and information should be combined to generate knowledge.
Machine readability	Knowledge must be understandable both by people and machines what requires standardization.
Context sensitivity	Smart services are context sensitive as individual requirements are satisfied: knowledge management must contribute to that.
Use context information	Specific context information should be abstracted for knowledge management support.
Real-time reaction	For smart services, reaction in real-time is partially necessary: a KMSSS must enable and support that.
Individual output	Depending on the smart service, context and requirements help to adapt output individually.
Value network	Knowledge is not only used across departments but also across participants of a value network.
Interfaces	The KMSSS should be connectable to other IS and tools.
Integrability	The KMSSS should be embedded adequately in existing IS and processes.
Security and privacy	Measures such as role-based authentication address security and privacy concerns; concepts and strategies for remote access are inevitable.

It is recommended that a KMSSS is not only used but that it is also reflected whether the KMSSS is still suitable for the offered smart services. Knowledge management is not only a topic in the operating level, but also in the management and strategic levels. Independent from the specific application of knowledge management it is highly important that it is oriented on the provided smart services and their customers.

The presented demonstration example shows that a tailored KMSSS is the prerequisite for offering smart maintenance services in the context of industrial applications. Different knowledge sources within a company as well as in the value network need to be considered and combined. It also shows that such smart services cannot be provided by a single partner but through interactions of the participants of a value network.

6 Limitations

We did not only search for publications dealing with smart services but also for ones that deal with digital services and electronic services. The second and third search terms were chosen because we assumed that, especially in earlier publications, it is already dealt with services according to the presented definition.

Nevertheless, it cannot be excluded that there are further search terms that partially also describe services that are smart in our understanding. Another point of the structured literature review is the considered databases. We assumed the eight chosen databases to be the most important ones in the field of IS Research (ISR). Although we found very relevant publications in these databases, it cannot be excluded that there are relevant articles in other databases. We decided whether a publication is relevant for our research or not, using characteristics presented at the beginning. From our point of view, it contains the relevant aspects of a smart service. Nevertheless, another definition might have led to another literature basis from which the reference model is derived.

Characteristics, key capabilities and technical conditions formed the basis for the developed reference model. A theoretic approach was taken to look at tailored KMSSS. As smart services are not only theoretic constructions but are also highly relevant in practice, interviews with experts can add additional aspects that are not yet considered. The cubic model was developed subsequently from requirements.

7 Conclusions and Outlook

We looked at knowledge management from a smart services' perspective. Publications that considered smart services were comprehensively reviewed to identify requirements for knowledge management. To ensure that the requirements named in the literature were identified in our research, a structured literature review was conducted.

Characteristics, capabilities and technical conditions of tailored KMSSS were identified. This kind of knowledge management differs because smart services are embedded in value networks. Usually, not a single company offers a smart service, but different participants are involved. Customers also form part of the value network because smart services are characterized by value co-creation. Participants can be located all over the world. Therefore, a KMSSS is not a local IS but globally used. Additionally, smart services often require actions in real-time or near real-time. Specific requirements regarding reliability arise from that. The possible input is manifold because smart services are manifold, too. Taking all aspects into account illustrates the complexity of a tailored KMSSS.

As smart services are a relatively new research field, there are only few best practice studies. The role of knowledge management within the field of smart services may change. Further research in this field is important for the development of this topic. As we focused on the design of tailored KMSSS, further approaches are interesting concerning technical realizations. How to embed new requirements in existing KMSSS is interesting for those who already use such IS.

A KMSSS must be a learning IS and continually be improved. It must not be a static IS, but a dynamic and living one. Knowledge management leads to improvements of provided smart services or even enables them. Additionally, processes between participants of the value network and inside a company are improved. As smart services are diverse, there is not the only one KMSSS that fits best for all types of smart services. Many different specifications exist for knowledge management characteristics. The reference model developed in our research illustrates the diversity of designs for tailored KMSSS. The recommendations derived from the comprehensive review emphasize the importance of the topic in practice.

Appendix (List of all 157 publications included in the literature review)

Abbate T, de Luca D, Gaeta A, Lepore M., Miranda S, Perano M (2015) Analysis of open innovation intermediaries platforms by considering the smart service system perspective. Procedia Manuf 3:3575–3582

Abdellatif A, Amor NB, Mellouli S (2013) An intelligent framework for e-government personalized services. In: Proceedings of the 14th Annual International Conference on Digital Government Research, pp 120–126

Adeleke IA, AbdulRahman A (2011) Co-creation of value: applying the paradigm to government e-service. In: Proceedings of the 2nd International Conference on Research and Innovation in Information Systems, pp 201–206

Al Nuaimi E, Al Neyadi H, Mohamed N, Al-Jaroodi J (2015) Applications of big data to smart cities. J Internet Serv Appl 6(25):1–15

Allmendinger G, Lombreglia R (2005) Four strategies for the age of smart services. Harv Bus Rev 83(10):131–145

Alti A, Laborie S, Roose P (2015) Cloud semantic-based dynamic multimodal platform for building mhealth context-aware services. In: Proceedings of the 11th IEEE International Conference on Wireless and Mobile Computing, Networking and Communications, pp 357–364

Anke J (2019) Design-integrated financial assessment of smart services. Electron Mark, 29(1):19–35

Anthopoulos L, Fitsilis P (2014) Exploring architectural and organizational features in smart cities. In: Proceedings of the 16th International Conference on Advanced Communication Technology, pp 190–194

Anthopoulos L, Janssen M, Weerakkody V (2016) Smart service portfolios: do the cities follow standards? In: Proceedings of the 25th International Conference Companion on World Wide Web, pp 357–362

Anttiroiko A-V, Valkama P, Bailey, SJ (2014) Smart cities in the new service economy: building platforms for smart services. AI Soc 29(3):323–334

Badii C, Bellini P, Cenni D, Difino A, Nesi P, Paolucci M (2017) Analysis and assessment of a knowledge based smart city architecture providing service APIs. Future Gener Comput Syst 75:14–29

Baldoni R, Mecella M, Querzoni L (2010) Smart services for home automation. Managing Concurrency and failures: new wine in old bottles?. In: Proceedings of the 5th International Conference on Pervasive Computing and Applications

Barile S, Polese F (2010) Smart service systems and viable service systems: applying systems theory to service science. Serv Sci 2(12):21–40

Batubara FR (2015) Balancing functionality, risk, and cost in smart service networks. In: Proceedings of the ICSOFT Doctoral Consortium, pp 7–14

Bedogni L, Bononi L, Di Felice M, D'Elia A, Mock R, Montori F, … Vergari F (2013) An interoperable architecture for mobile smart services over the Internet of Energy. In: Proceedings of the 14th IEEE International Symposium on 'A World of Wireless, Mobile and Multimedia Networks', pp 298–303

Berna-Martinez J, Macia-Perez F, Ramos-Morillo H, Gilart-Iglesias V (2006) Distributed robotic architecture based on smart services. In: Proceedings of the IEEE International Conference on Industrial Informatics, pp 480–485

Beverungen D, Müller O, Matzner M, Mendling J, vom Brocke J (2017) Conceptualizing smart service systems. Electron Mark 29(1):7–18

Böcker M, Rodriguez-Ascaso A, Huttenrauch H, Schneider M, Pluke M, Zetterstrom E (2010) Identifying Enablers for Future e-Services. In: Proceedings of the 4th International ICST Conference on Pervasive Computing Technologies for Healthcare

Brotman R, Burleson W, Forlizzi J, Heywood W, Lee J (2015) Building change: constructive design of smart domestic environments for goal achievement. In: Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems, pp 3083–3092

Buchanan S, McMenemy D (2012) Digital service analysis and design: the role of process modelling. Int J Inform Manag 32(3):251–256

Buettner R (2016) Innovative personality-based digital services. In: Proceedings of the Pacific Asia Conference on Information Systems, paper 278

Bullinger HJ, Neuhuttler J, Nagele R, Woyke I (2017) Collaborative development of business models in smart service ecosystems. In: Proceedings of the IEEE Portland International Conference Management of Engineering and Technology

Byun J, Park S (2011) Development of a self-adapting intelligent system for building energy saving and context-aware smart services. IEEE Trans Consum Electron 57(1):90–98

Calza F, Gaeta M, Loia V, Orciuoli F, Piciocchi P, Rarità L, … Tommasetti A (2015) Fuzzy consensus model for governance in smart service systems. Procedia Manuf 3:3567–3574

Cardozo N, Clarke S (2015) Language design for developing smart adaptive services. In: Proceedings of the 1st IEEE International Smart Cities Conference

Cellary W (2013) Smart governance for smart industries. In: Proceedings of the 7th International Conference on Theory and Practice of Electronic Governance, pp 91–93

Chatterjee P, Armentano RL (2015) Internet of Things for a smart and ubiquitous ehealth system. In: Proceedings of the 7th International Conference on Computational Intelligence and Communication Networks, pp 903–907

Chen J, Yuan L, Mingins C (2012) NeSD: Towards a new e-services development framework. In: Proceedings of the 11th Wuhan International Conference on e-Business, pp 555–562

Chu Y-Y, Lin S-W (2011) Network ontology and dynamics analysis for collaborative innovation in digital services. In: Proceedings of the IEEE Portland International Center of Management of Engineering and Technology

Ciortea A, Boissier O, Zimmermann A, Florea AM (2016) Responsive decentralized composition of service mashups for the Internet of Things. In: Proceedings of the 6th International Conference on the Internet of Things, pp 53–61

Da Q, Guo Y, Li D (2018) Smart Service System of the Internet of Things. In: IEEE International Conference on Consumer Electronics, pp 1–2

Dawid H, Decker R, Hermann T, Jahnke H, Klat W, König R, Stummer C (2016) Management science in the era of smart consumer products: challenges and research perspectives. Cent Eur J Oper Res 25(1):203–230

De Oliveira VC, Silva JR (2015) A service-oriented framework to the design of information system service. J Serv Sci Res 7(2):55–96

Delfanti M, Esposito G, Olivieri V, Zaninelli D (2015) SCUOLA project: The 'hub of smart services' for cities and communities. In: Proceedings of the 4th International Conference on Renewable Energy Research and Applications, pp 1502–1506

Domingues J, Damaso A, Rosa N (2010) Smart: service model for integrating wireless sensor networks and the internet. In: Proceedings of the 16th IEEE International Conference on Parallel and Distributed Systems, pp 365–372

Eniser HF, Sen A, Polat SO (2018) Fancymock: creating virtual services from transactions. In: Proceedings of the 33rd Annual ACM Symposium on Applied Computing, pp 1576–1578

Fan M, Sun J, Zhou B, Chen M (2016) The smart health initiative in China: the case of Wuhan, Hubei Province. J Med Syst 40(62):1–17

Fan Z, Chen Q, Kalogridis G, Tan S, Kaleshi D (2012) The power of data: data analytics for M2M and smart grid. In: Proceedings of the 3rd IEEE PES Innovative Smart Grid Technologies Europe

Ferretti S, D'Angelo G (2016) Smart shires: the revenge of countrysides. In: Proceedings of the 21st IEEE Symposium on Computers and Communication, pp 756–759

Ferretti S, D'Angelo G, Ghini V (2016) Smart multihoming in smart shires: mobility and communication management for smart services in countrysides. In: Proceedings of the 21st IEEE Symposium on Computers and Communication, pp 970–975

Georgakopoulos D, Jayaraman PP (2016) Internet of Things: from internet scale sensing to smart services. Comput 98(10):1041–1058

Geum Y, Jeon H, Lee H (2016) Developing new smart services using integrated morphological analysis: integration of the market-pull and technology-push approach. Serv Bus 10(3):531–555

Gillig H, Sailer K (2012) User involvement in the innovation process: development of a framework for e-services. In: Proceedings of the 18th International Conference on Engineering, Technology and Innovation

Gretzel U, Sigala M, Xiang Z, Koo C (2015) Smart tourism: foundations and developments. Electron Mark 25(3):179–188

Guo Y, Zhu H, Yang L (2017) Smart service system (sss): A novel architecture enabling coordination of heterogeneous networking technologies and devices for internet of things. China Commun 14(3):130–144

Hamdan D, Aktouf O-E-K, Parissis I, Hijazi A, Sarkis M, El Hassan B (2012) Smart service for fault diagnosis in wireless sensor networks. In: Proceedings of the 6th International Conference on Next Generation Mobile Applications, Services and Technologies, pp 211–216

Haubeck C, Lamersdorf W, Fay A (2017) A knowledge carrying service-component architecture for smart cyber physical systems. In: International Conference on Service-Oriented Computing, pp 270–282

He J, Zhang Y, Huang G, Cao J (2012) A smart web service based on the context of things. ACM Trans Internet Technol 11(3):1–23

Herterich MM (2017) On the design of digitized industrial products as key resources of service platforms for industrial service innovation. In: International Conference on Design Science Research in Information System and Technology, pp 364–380

Hirt R, Kühl N (2018) Cognition in the era of smart service systems: inter-organizational analytics through meta and transfer learning

Hirt R, Kühl N, Schmitz B, Satzger G (2018) Service-oriented cognitive analytics for smart service systems: a research agenda, pp 1622–1629

Holgado M, Macchi M (2014) Exploring the role of e-maintenance for value creation in service provision. In: Proceedings of the International ICE Conference on Engineering, Technology and Innovation, pp 174–183

Hong L, She Z, Ye J, Chen X (2014) An exploration research of establishing e-service dimensions model by building up service Qquality indexes based on process interaction. In: Proceedings of the 11th International Conference on Service Systems and Service Management

Huang T-L (2017) Creating a commercially compelling smart service encounter. Serv Bus 12(2):357–377

Huang M, Bai Y, Chen Y, Sun B (2017) A Ddistributed proactive service framework for crowd-sensing process. In: 2017 IEEE 13th International Symposium on Autonomous Decentralized System, pp 68–74

Hussein D, Han SN, Lee GM, Crespi N, Bertin E (2017) Towards a dynamic discovery of smart services in the social internet of things. Comput Electr Eng 58:429–443

Jerald AV, Rabara SA, Bai DP (2016) Secure IoT architecture for integrated smart services environment. In: Proceedings of the 3rd International Conference on Computing for Sustainable Global Development, pp 800–805

Jerald AV, Rabara SA, Bai DP (2017) Algorithmic approach to security architecture for integrated IoT smart services environment. In: 2017 World Congress on Computing and Communication Technologies, pp 24–29

Kamp B, Ochoa A, Diaz J (2016) Smart servitization within the context of industrial user-supplier relationships: contingencies according to a machine tool manufacturer. Int J Interact Des Manuf 11(3):651–663

Kennedy D, Keskin T (2016) A pricing model for the Internet of Things enabled smart service systems. In: Proceedings of the 49th Hawaii International Conference on System Sciences, pp 1782–1789

Keskin T, Kennedy D (2015) Strategies in smart service systems enabled multi-sided markets: business models for the Internet of Things. In: Proceedings of the 48th Hawaii International Conference on System Sciences, pp 1443–1452

Kim E (2017) Smart city service platform associated with smart home. In: 2017 International Conference on Information Networking, pp 608–610

Kim E, Chung K, Jeong T (2017) Self-certifying ID based trustworthy networking system for IoT smart service domain. In: 2017 International Conference on Information and Communication Technology Convergence, pp 1299–1301

Kim MJ, Lee JH, Wang X, Kim JT (2015) Health smart home services incorporating a MAR-based energy consumption awareness system. J Intell Robot Syst 79(3):523–535

Klein MM, Biehl SS, Friedli T (2018) Barriers to smart services for manufacturing companies–an exploratory study in the capital goods industry. J Bus Ind Marketing, 33(6):846–856

Knote R, Blohm I (2016) It's not about having ideas – it's about making ideas happen! fostering exploratory innovation with intrapreneur accelerator. In: Proceedings of the 24th European Conference on Information Systems, paper 59

Kölmel B, Bulander R (2015) Sustainability and competitiveness through digital product-service-systems. In: Proceedings of the eChallenges e-2015 Conference

Korzun DG, Borodin AV, Timofeev IA, Paramonov IV, Balandin SI (2015) Digital assistance services for emergency situations in personalized mobile healthcare: smart space based approach. In: Proceedings of the International Conference on Biomedical Engineering and Computational Technologies, pp 62–67

Kryvinska N, Strauss C, Auer L, Zinterhof P (2008) Conceptual framework for services creation/development environment in telecom domain. In: Proceedings of the 10th International Conference on Information Integration and Web-based Applications & Services, pp 324–331

Kuebel H, Zarnekow R (2015) Exploring platform adoption in the smart home case. In: Proceedings of the 36th International Conference on Information Systems

Kwak J-Y, Kim S-T, Lee KH, Yang S (2014) Service-oriented networking platform on smart devices. IET Commun 9(3):429–439

Kynsilehto M, Olsson T (2011) Intelligent ambient technology — friend or foe?. In: Proceedings of the 15th International Academic MindTrek Conference, pp 99–106

Kynsilehto M, Olsson T (2012) Checkpoints, hotspots and standalones — placing smart services over time and place. In: Proceedings of the 7th Nordic Conference on Human-Computer Interaction: Making Sense Through Design, pp 209–218

Laubis K, Konstantinov M, Simko V, Gröschel A, Weinhardt C (2019) Enabling crowdsensing-based road condition monitoring service by intermediary. Electron Mark 29(1):125–140

Lê Tuán A, Mau Quoc HN, Serrano M, Hauswirth M, Soldatos J, Papaioannou T, Aberer K (2012) Global sensor modeling and constrained application methods enabling cloud-based open space smart services. In: Proceedings of the 9th International Conference on Ubiquitous Intelligence and Computing and 9th International Conference on Autonomic and Trusted Computing, pp 196–203

Lebedev N, Timofeev I, Zavialova I (2016) Design and implementation of the first aid assistance service based on smart-m3 platform. In: Proceedings of the 18th Conference of Open Innovations Association and Seminar on Information Security and Protection of Information Technology, pp 174–180

Lee B-H, Lim S-H, Kim J-H (2010) Scalable real-time monitoring system for ubiquitous smart space. Inform Process Lett 110(8–9):294–299

Lee H, Seol H, Min H, Geum Y (2016) The identification of new service opportunities: a cCase-based morphological analysis. Serv Bus 11(1):191–206

Lee JY, Kim MK, La HJ, Kim SD (2012) A software framework for enabling smart services. In: Proceedings of the 5th IEEE International Conference on Service-Oriented Computing and Applications, pp 55–62

Lee N, Lee H, Lee H, Ryu W (2015) Implementation of smart home service over web of object architecture. In: Proceedings of the 6th International Conference on Information and Communication Technology Convergence, pp 1215–1219

Lee C, Ofek E, Steenburgh TJ (2017) Personal and social usage: the origins of active customers and ways to keep them engaged. Manag Sci 64(6):2473–2495

Lesjak C, Hein D, Hofmann M, Maritsch M, Aldrian A, Priller P, … Pregartner G (2015) Securing smart maintenance services: hardware-security and TLS for MQTT. In: Proceedings of the 13th International Conference on Industrial Informatics, pp 1243–1250

Lesjak C, Ruprechter T, Bock H, Haid J, Brenner E (2014) ESTADO — enabling smart services for industrial equipment through a secured, transparent and ad-hoc data transmission online. In: Proceedings of the 9th International Conference for Internet Technology and Secured Transactions, pp 171–177

Li Y, Wan Z, Huang J, Chen J, Huang Z, Zhong N (2015) A smart hospital information system for mental disorders. In: Proceedings of the 2015 IEEE/WIC/ACM International Conference on Web Intelligence and Intelligent Agent Technology, pp 321–324

Lim C, Maglio PP (2018) Data-driven understanding of smart service systems through text mining. Serv Sci 10(2):154–180

Ma M, Preum SM, Stankovic JA (2017) Cityguard: A watchdog for safety-aware conflict detection in smart cities. In: Proceedings of the Second International Conference on Internet-of-Things Design and Implementation, pp 259–270

Ma X, Qian K, Dai X, Fang F, Xing Y (2010) Framework design for distributed service robotic systems. In: Proceedings of the 5th IEEE Conference on Industrial Electronics and Applications, pp 234–239

Maglio PP, Lim CH (2016) Innovation and big data in smart service systems. J Innov Manag 4(1):11–21

Maleki E, Belkadi F, Bernard A (2018) Industrial product-service system modelling base on systems engineering: application of sensor integration to support smart services. IFAC P OnLine, 51(11):1586–1591

Maleshkova M, Philipp P, Sure-Vetter Y, Studer R (2016) Smart web services (SmartWS) — the future of services on the web. Trans Adv Res 12(1):15–26

Martin N, Gregor S, Hart D (2004) Using a common architecture in Australian e-government – the case of smart service queensland. In: Proceedings of the 6th International Conference on Electronic Commerce, pp 516–525

Massink M, Harrison M, Latella D (2010) Scalable analysis of collective behaviour in smart service systems. In: Proceedings of the ACM Symposium on Applied Computing, pp 1173–1180

Mathes M, Stoidner C, Schwarzkopf R, Heinzl S, Dörnemann T, Dohmann H, Freisleben B (2009) Time-constrained services: a framework for using real-time web services in industrial automation. Serv Oriented Comput Appl 3(4):239–262

Maurer F, Schumacher J (2018) Organizational robustness and resilience as catalyst to boost innovation in smart service factories of the future. In: 2018 IEEE International Conference on Engineering, Technology and Innovation

Mihaylov M, Mihovska A, Kyriazakos S, Prasad R (2015) Interoperable ehealth platform for personalized smart services. In: Proceedings of the IEEE International Conference on Communication Workshop, pp 240–245

Mihovska A, Kyriazakos S, Prasad R, Pejanovic-Djurisic M, Poulkov V (2015) Integration of wireless and data technologies for personalized smart applications. In: Proceedings of the 14th Wireless Telecommunications Symposium (WTS), pp 304–311

Mikusz M (2017) Value-in-context with service innovation in the digital age: a service-dominant logic perspective. In: Proceedings of the 50th Hawaii International Conference on System Sciences, pp 1267–1276

Mittag T, Rabe M, Gradert T, Kühn A, Dumitrescu R (2018) Building blocks for planning and implementation of smart services based on existing products. Procedia CIRP, 73:102–107

Mo T, Li W, Chu W, Wu Z (2010) CABS3: context-awareness based smart service system. In: Proceedings of the 6th International Conference on Wireless Communications, Networking and Mobile Computing, pp 1834–1837

Moawad A, Hartmann T, Fouquet F, Klein J, Le Traon Y (2015) Adaptive blurring of sensor data to balance privacy and utility for ubiquitous services. In: Proceedings of the 30th Annual ACM Symposium on Applied Computing, pp 2271–2278

Motahari Nezhad HR, Shwartz L (2017) Towards open smart services platform. In: Proceedings of the 50th Hawaii international conference on system sciences, pp 1103–1109

Mukudu N, Ventura N, Mwangama J, Elmangoush A, Steinke R, Magedanz T (2016) Prototyping smart city applications over large scale M2M testbed. In: Proceedings of the 2016 IST-Africa Week Conference

Nakajima H, Shiga T, Hata Y (2012) Systems Health Care: Coevolutionary Integration of Smart Devices and Smart Services. In Proceedings of the Annual SRII Global Conference, pp 231–236

Odefey U, Baumann F, Grünert G, Hudert S, Zimmermann M, Falkenthal M, Leymann F (2018) Manufacturing smart services for automotive production lines. In: Proceeding of the 18. Internationales Stuttgarter Symposium, pp 813–825

Oh JS, Park JS, Kwon JR (2010) Ubiquitous infrastructure and smart service on city gas environments in Korea. In: Proceedings of the 5th International Conference on Future Information Technology

Oslislo LJ, Talevski A, Karduck AP (2011) SMART CAMP: benefits of media and smart service convergence. In: Proceedings of the 25th IEEE Workshops of International Conference on Advanced Information Networking and Applications, pp 763–768

Paluch S, Wünderlich NV (2016) Contrasting risk perceptions of technology-based service innovations in inter-organizational settings. J Bus Res 69(7):2424–2431

Panjwani M, Jäntti M (2017) Data protection & security challenges in digital & it services: a case study. In: 2017 International Conference on Computer and Applications, pp 379–383

Pao S-Y, Reben AJ, Rayes A (2011) MoSS: mobile smart services for ubiquitous network management. In: Proceedings of the International Conference on Collaboration Technologies and Systems, pp 48–52

Park H, Hwang S, Won M, Park T (2017) Activity-aware sensor cycling for human activity monitoring in smart homes. IEEE Commun Lett 21(4):757–760

Pereira, C., Cardoso, J., Aguiar, A., and Morla, R. (2018) Benchmarking pub/sub IoT middleware platforms for smart services. J Reliab Intell Environ 4(1):25–37

Perera C, Zaslavsky A, Christen P, Georgakopoulos D (2014) Sensing as a service model for smart cities supported by Internet of Things. Trans Emerg Telecommun Technol 25(1):81–93

Pistofidis P, Emmanouilidis C (2012) Developing advanced context aware tools for mobile maintenance. In: Proceedings of the 2nd IFAC Workshop on Advanced Maintenance Engineering, Services and Technology, pp 133–138

Pourzolfaghar Z, Helfert M (2017) Taxonomy of smart elements for designing effective services. In: 23rd Americas Conference on Information Systems, paper 16

Priller P, Aldrian A, Ebner T (2014) Case study: from legacy to connectivity: migrating industrial devices into the world of smart services. In: Proceedings of the 19th IEEE Emerging Technology and Factory Automation

Rantala K, Karjaluoto H (2017) Combining digitization with healthcare service processes: value co-creation opportunities through standard work. In: Proceedings of the 2017 Bled eConference, paper 18

Ren J, Ma J, Huang R, Jin Q, Chen Z (2014) A management system for cyber individuals and heterogeneous data. In: Proceedings of the 11th IEEE International Conference on Ubiquitous Intelligence and Computing and 11th IEEE International Conference on Autonomic and Trusted Computing and 14th IEEE International Conference on Scalable Computing and Communications and Its Associated Workshops, pp 88–95

Rizk A, Bergvall-Kåreborn B, Elragal A (2017) Digital service innovation enabled by big data analytics – a review and the way forward. In: Proceedings of the 50th Hawaii International Conference on System Sciences, pp1247–1256

Roduner C, Langheinrich M (2010) BIT — a framework and architecture for providing digital services for physical products. In: Proceedings of the Internet of Things Conference, pp 170–177

Sakakibara S, Saiki S, Nakamura M, Matsumoto S (2016) Indoor environment sensing service in smart City using autonomous sensor box. In: Proceedings of the 15th IEEE/ACIS International Conference on Computer and Information Science

Saunila M, Rantala T, Ukko J (2017) Characteristics of customer value creation in digital services. J Serv Sci Res 9(2):239–258

Savarino P, Abramovici M, Göbel JC, Gebus P (2018) Design for reconfiguration as fundamental aspect of smart products. Procedia CIRP 70(1):374–379

Seeliger R, Krauss C, Wilson A, Zwicklbauer M, Arbanowski S (2015) Towards personalized smart city guide services in future internet environments. In: Proceedings of the 24th International Conference on World Wide Web, pp 563–568

Singhai AJ, Faizan D (2016) Transition of indian ICT processes to smart e-services-way ahead. In: Proceedings of the 5th International Conference on Advances in Computing, Communications and Informatics, pp 1479–1486

Smirnov AV, Kashevnik AM, Ponomarev AV, Savosin SV (2015) Ontology-based organization of interactions between services in the smart space for hybrid system control. Sci Tech Inf Process 42(5):367–374

Smith G, Ofe HA, Sandberg J (2016) Digital service innovation from open data: exploring the value proposition of an open data marketplace. In: Proceedings of the 49th Hawaii International Conference on System Sciences, pp 1277–1286

Son J-Y, Park J-H, Moon K-D, Lee Y-H (2011) Resource-aware smart home management system by constructing resource relation graph. IEEE Trans Consum Electron 57(3):1112–1119

Song T, Cai J, Chahine T, Li L (2017) Towards smart cities by Internet of Things (IoT) — a silent revolution in China. J Knowl Econ

Spottke B, Eck A, Wulf J (2016) A socio-technical approach to study consumer-centric information systems. In: Proceedings of the 37th International Conference on Information Systems, paper 12

Stöhr C, Janssen M, Niemann J, Reich B (2018) Smart services. Procedia Soc Behav Sci 238:192–198

Strüker J, Kerschbaum F (2012) From a barrier to a bridge: data-privacy in deregulated smart grids. In: Proceedings of the 33rd International Conference on Information Systems

Tang Q, Guo Y (2018) Research on intelligence service model for Internet of Things. In: 2018 International Conference on Network Infrastructure and Digital Content, pp 250–255

Tantatsanawong P, Kawtrakul A, Lertwipatrakul W (2011) Enabling future education with smart services. In: Proceedings of the Annual SRII Global Conference, pp 550–556

Theocharis SA, Tsihrintzis GA (2013) Personalization as a means to improve e-services. In: Proceedings of the 2nd International Conference on Computer, Information and Telecommunication Systems

Tianyong W, Zhengliang X, Gel G (2006) Development and strategy of knowledge management for e-services. In: Proceedings of the International Conference on Service Systems and Service Management

Tien JM (2012) The next industrial revolution: Integrated Services and Goods. J Syst Sci Syst Eng 21(3):257–296

Töytäri P, Turunen T, Klein M, Eloranta V, Biehl S, Rajala R, Hakanen E (2017) Overcoming institutional and capability barriers to smart services. In: Proceedings of the 50th Hawaii International Conference on System Sciences, pp 1642–1651

Tsai MF, Kiong YC, Sinn A (2018) Smart service relying on Internet of Things technology in parking systems. J of Supercomput 74(9):4315–4338

Vogel B, Gkouskos D (2017) An open architecture approach: towards common design principles for an iot architecture. In: Proceedings of the 11th European Conference on Software Architecture, pp 85–88

Walderhaug S, Auran PG, Berre AJ, Yin D, Passano E, Lie H, ... Langlo JA (2018) Towards precision fishery: standardized modelling of smart services in the fishery domain. In: Proceedings of the 12th European Conference on Software Architecture: Companion Proceedings

Wang C, Akella R, Ramachandran S, Hinnant D (2011) Knowledge extraction and reuse within "smart" service centers. In: Proceedings of the Annual SRII Global Conference, pp 163–176

Wang Y, Taher Y, van den Heuvel W-J (2012) Towards smart service networks: an interdisciplinary service assessment metrics. In: Proceedings of the 16th IEEE International Enterprise Distributed Object Computing Conference Workshops, pp 94–103

Weijie C, Tong M, Jie C, Yuan W, Jingmin X, Weiping L, Huiping L (2012) A context-aware services development model. In: Proceedings of the International Joint Conference on Service Sciences, pp 194–199

Westwood JA, Cazier JA (2016) Work-life optimization: using big data and analytics to facilitate work-life balance. In: Proceedings of the 49th Hawaii International Conference on System Sciences, pp 1701–1709

Wiegard RB, Breitner MH (2019) Smart services in healthcare: a risk-benefit-analysis of pay-as-you-live services from customer perspective in Germany. Electron Mark 29(1):107–123

Williams K, Chatterjee S, Rossi M (2008) Design of emerging digital services: a taxonomy. Eur J Inform Syst 17(5):505–517

Wünderlich NV, Heinonen K, Ostrom AL, Patricio L, Sousa R, Voss C, Lemmink JG (2015) 'Futurizing' smart service: implications for service researchers and managers. J Serv Marketing 29(6–7):442–447

Wünderlich NV, von Wangenheim F, Bitner MJ (2012) High tech and high touch: a framework for understanding user attitudes and behaviors related to smart interactive services. J Serv Res 16(1):3–20

Wutzler M, Springer T, Schill A (2017) RoleDiSCo: a middleware architecture and implementation for coordinated on-demand composition of smart service systems in decentralized environments. In: 2017 IEEE 2nd International Workshops on Foundations and Applications of Self Systems, pp 39–44

Wutzler M, Weissbach M, Springer T (2017) Role-based models for building adaptable collaborative smart service systems. In: Proceedings of the IEEE International Conference on Smart Computing, pp 1–6

Yachir A, Tari K, Amirat Y, Chibani A, Badache N (2009) QoS based framework for ubiquitous robotic services composition. In: Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, pp 2019–2026

Yang QZ, Miao CY, Shen ZQ (2015) Digital services innovation for aging-in-place. In: Proceedings of the 22nd International Conference on Industrial Engineering and Engineering Management, pp 569–573

Ye F, Qian Y (2017) A security architecture for networked Internet of Things devices. In: Proceedings of the IEEE Global Communications Conference, pp 1–6

Yong M, Hui-ying C (2013) Study on the value promotion and development strategy of smart tourism. In: Proceedings of the 12th Wuhan International Conference on e-Business, paper 45

Yu C-C (2004) A web-based consumer-oriented intelligent decision support system for personalized e-services. In: Proceedings of the 6th International Conference on Electronic Commerce, pp 429–437

Zhang J, Qi B (2011) Studies on interactive service platform for smart grid. In: Proceedings of the IEEE PES Innovative Smart Grid Technologies Asia, pp 213–216

Zo H (2003) Personalization vs. customization: which is more effective in e-services?. In: Proceedings of the 9th Americas Conference on Information Systems, paper 32

References

Abbate T, de Luca D, Gaeta A, Lepore M, Miranda S, Perano M (2015) Analysis of open innovation intermediaries platforms by considering the smart service system perspective. Procedia Manuf 3:3575–3582

Al Nuaimi E, Al Neyadi H, Mohamed N, Al-Jaroodi J (2015) Applications of big data to smart cities. J Internet Serv Appl 6(25):1–15

Alavi M, Leidner DE (2001) Knowledge management and knowledge management systems: conceptual foundations and research issues. MISQ 26(1):107–136

Alahmadi M, Qureshi MRJ (2015) Improved model to test applications using smart services. Sci Int 27(3):2275–2280

Allmendinger G, Lombreglia R (2005) Four strategies for the age of smart services. Harv Bus Rev 83(10):131–145

Alti A, Laborie S, Roose P (2015) Cloud semantic-based dynamic multimodal platform for building mhealth context-aware services. In: Proceedings of the 11th IEEE International Conference on Wireless and Mobile Computing, Networking and Communications, pp 357–364

Anttiroiko A-V, Valkama P, Bailey, SJ (2014) Smart cities in the new service economy: building platforms for smart services. AI Soc 29(3):323–334

Badii C, Bellini P, Cenni D, Difino A, Nesi P, Paolucci M (2017) Analysis and assessment of a knowledge based smart city architecture providing service APIs. Future Gener Comput Syst 75:14–29

Bagheri S, Kuster RJ, Trienekens JJM, van der Zandt HVN (2016) Classification framework of knowledge transfer issues across value networks. Procedia CIRP 47:382–387

Baldoni R, Mecella M, Querzoni L (2010) Smart services for home automation. Managing Concurrency and failures: new wine in old bottles?. In: Proceedings of the 5th International Conference on Pervasive Computing and Applications

Barile S, Polese F (2010) Smart service systems and viable service systems: applying systems theory to service science. Serv Sci 2(12):21–40

Batubara FR (2015) Balancing functionality, risk, and cost in smart service networks. In: Proceedings of the ICSOFT Doctoral Consortium, pp 7–14

Becker J, Delfmann P (2007) Reference Modeling – Efficient Information Systems Design Through Reuse of Information Models, Physica-Verlag HD

Bedogni L, Bononi L, Di Felice M, D'Elia A, Mock R, Montori F, … Vergari F (2013) An interoperable architecture for mobile smart services over the Internet of Energy. In: Proceedings of the 14th IEEE International Symposium on 'A World of Wireless, Mobile and Multimedia Networks', pp 298–303

Berna-Martinez J, Macia-Perez F, Ramos-Morillo H, Gilart-Iglesias V (2006) Distributed robotic architecture based on smart services. in Proceedings of the IEEE International Conference on Industrial Informatics, Singapore, Singapore, 16-18 August 2006. pp 480–485

Beverungen D, Müller O, Matzner M, Mendling J, vom Brocke J (2017) Conceptualizing smart service systems. Electron Mark 29(1):7–18

Beverungen D, Lüttenberg H, Wolf V (2018) Recombinant service systems engineering. Bus Inf Syst Eng 60(5), 377–391

Böhmann T, Leimeister JM, Möslein K (2018) The new fontiers of service systems engineering. Bus Inf Syst Eng 60(5): 373–375

Bullinger HJ, Neuhuttler J, Nagele R, Woyke I (2017) Collaborative development of business models in smart service ecosystems. In: Proceedings of the IEEE Portland International Conference Management of Engineering and Technology

Byun J, Park S (2011) Development of a self-adapting intelligent system for building energy saving and context-aware smart services. IEEE Trans Consum Electron 57(1):90–98

Calza F, Gaeta M, Loia V, Orciuoli F, Piciocchi P, Rarità L, … Tommasetti A (2015) Fuzzy consensus model for governance in smart service systems. Procedia Manuf 3:3567–3574

Cellary W (2013) Smart governance for smart industries. In: Proceedings of the 7th International Conference on Theory and Practice of Electronic Governance, pp 91–93

Chatterjee P, Armentano RL (2015) Internet of Things for a smart and ubiquitous ehealth system. In: Proceedings of the 7th International Conference on Computational Intelligence and Communication Networks, pp 903–907

Chu Y-Y, Lin S-W (2011) Network ontology and dynamics analysis for collaborative innovation in digital services. In: Proceedings of the IEEE Portland International Center of Management of Engineering and Technology

Ciortea A, Boissier O, Zimmermann A, Florea AM (2016) Responsive decentralized composition of service mashups for the Internet of Things. In: Proceedings of the 6th International Conference on the Internet of Things, pp 53–61

Davenport TH, Prusak L (1998) Working knowledge: how organizations manage what they know, Harvard Business Press

Dawid H, Decker R, Hermann T, Jahnke H, Klat W, König R, Stummer C (2016) Management science in the era of smart consumer products: challenges and research perspectives. Cent Eur J Oper Res 25(1):203–230

De Oliveira VC, Silva JR (2015) A service-oriented framework to the design of information system service. J Serv Sci Res 7(2):55–96

Delfanti M, Esposito G, Olivieri V, Zaninelli D (2015) SCUOLA project: The 'hub of smart services' for cities and communities. In: Proceedings of the 4th International Conference on Renewable Energy Research and Applications, pp 1502–1506

Demirkan H, Bess C, Spohrer J, Rayes A, Allen D, Moghaddam Y (2015) Innovations with smart service systems: analytics, big data, cognitive assistance, and the internet of everything. Commun. Assoc Inf Syst 37(1):733–752

Dreyer S, Olivotti D, Lebek B, Breitner MH (2019) Focusing the customer through smart services: a literature review. Electron Mark 29(1):55–78

Fahey L, Srivastava R, Sharon JS, Smith DE (2001) Linking e-business and operating processes: the role of knowledge management. IBM Syst J 40(4):889–907

Fan M, Sun J, Zhou B, Chen M (2016) The smart health initiative in China: the case of Wuhan, Hubei Province. J Med Syst 40(62):1–17

Fan Z, Chen Q, Kalogridis G, Tan S, Kaleshi D (2012) The power of data: data analytics for M2M and smart grid. In: Proceedings of the 3rd IEEE PES Innovative Smart Grid Technologies Europe

Ferretti S, D'Angelo G, Ghini V (2016) Smart multihoming in smart shires: mobility and communication management for smart services in countrysides. In: Proceedings of the 21st IEEE Symposium on Computers and Communication, pp 970–975

Gavrilova T, Kokoulina L (2015) Smart services classification framework. In: Proceedings of the Federated Conference on Computer Science and Information Systems, pp 203–207

Georgakopoulos D, Jayaraman PP (2016) Internet of Things: from internet scale sensing to smart services. Comput 98(10):1041–1058

Gretzel U, Sigala M, Xiang Z, Koo C (2015) Smart tourism: foundations and developments. Electron Mark 25(3):179–188

He J, Zhang Y, Huang G, Cao J (2012) A smart web service based on the context of things. ACM Trans Internet Technol 11(3):1–23

Holgado M, Macchi M (2014) Exploring the role of e-maintenance for value creation in service provision. In: Proceedings of the International ICE Conference on Engineering, Technology and Innovation, pp 174–183

Huang T-L (2017) Creating a commercially compelling smart service encounter. Serv Bus 12(2):357–377

Hussein D, Han SN, Lee GM, Crespi N, Bertin E (2017) Towards a dynamic discovery of smart services in the social Internet of Things. Comput Electr Eng 58:429–443

Jerald AV, Rabara SA, Bai DP (2016) Secure IoT architecture for integrated smart services environment. In: Proceedings of the 3rd International Conference on Computing for Sustainable Global Development, pp 800–805

Keskin T, Kennedy D (2015) Strategies in smart service systems enabled multi-sided markets: business models for the Internet of Things. In: Proceedings of the 48th Hawaii International Conference on System Sciences, pp 1443–1452

Kim MJ, Lee JH, Wang X, Kim JT (2015) Health smart home services incorporating a MAR-based energy consumption awareness system. J Intell Robot Syst 79(3):523–535

Korzun DG, Borodin AV, Timofeev IA, Paramonov IV, Balandin SI (2015) Digital assistance services for emergency situations in personalized mobile healthcare: smart space based approach. In: Proceedings of the International Conference on Biomedical Engineering and Computational Technologies, pp 62–67

Kwak J-Y, Kim S-T, Lee KH, Yang S (2014) Service-oriented networking platform on smart devices. IET Commun 9(3):429–439

Kynsilehto M, Olsson T (2011) Intelligent ambient technology — friend or foe?. In: Proceedings of the 15th International Academic MindTrek Conference, pp 99–106

Kynsilehto M, Olsson T (2012) Checkpoints, hotspots and standalones — placing smart services over time and place. In: Proceedings of the 7th Nordic Conference on Human-Computer Interaction: Making Sense Through Design, pp 209–218

Lee JY, Kim MK, La HJ, Kim SD (2012) A software framework for enabling smart services. In: Proceedings of the 5th IEEE International Conference on Service-Oriented Computing and Applications, pp 55–62

Lesjak C, Ruprechter T, Bock H, Haid J, Brenner E (2014) ESTADO — enabling smart services for industrial equipment through a secured, transparent and ad-hoc data transmission online. In: Proceedings of the 9th International Conference for Internet Technology and Secured Transactions, pp 171–177

Li Y, Wan Z, Huang J, Chen J, Huang Z, Zhong N (2015) A smart hospital information system for mental disorders. In: Proceedings of the 2015 IEEE/WIC/ACM International Conference on Web Intelligence and Intelligent Agent Technology, pp 321–324

Liao SH (2003) Knowledge management technologies and applications — literature review from 1995 to 2002. Expert Syst Appl 25(2):155–164

Liu S, Delibasic B, Butel L, Han X (2017) Sustainable knowledge-based decision support systems (DSS): perspectives, new challenges and recent advance. Ind Manag Data Syst 117(7):1318–1322

Ma X, Qian K, Dai X, Fang F, Xing Y (2010) Framework design for distributed service robotic systems. In: Proceedings of the 5th IEEE Conference on Industrial Electronics and Applications, pp 234–239

Maleshkova M, Philipp P, Sure-Vetter Y, Studer R (2016) Smart web services (SmartWS) — the future of services on the web. The IPSI BgD Trans Adv Res 12(1):15–26

Martin N, Gregor S, Hart D (2004) Using a common architecture in Australian e-government — the case of smart service Queensland. In: Proceedings of the 6th International Conference on Electronic Commerce, pp 516–525

Massey AP, Montoya-Weiss MM, O'Driscoll TM (2002) Performance-centered design of knowledge-intensive processes. J Manag Inf Syst 18(4):37–58

Massink M, Harrison M, Latella D (2010) Scalable analysis of collective behaviour in smart service systems. In: Proceedings of the ACM Symposium on Applied Computing, pp 1173–1180

Mathes M, Stoidner C, Schwarzkopf R, Heinzl S, Dörnemann T, Dohmann H, Freisleben B (2009) Time-constrained services: a framework for using real-time web services in industrial automation. Service Oriented Comput. and Appl. 3(4):239–262

Mihovska A, Kyriazakos S, Prasad R, Pejanovic-Djurisic M, Poulkov V (2015) Integration of wireless and data technologies for personalized smart applications. In: Proceedings of the 14th Wireless Telecommunications Symposium (WTS), pp 304–311

Mikusz M (2017) Value-In-Context with Service Innovation in the Digital Age: A Service-Dominant Logic Perspective. In: Proceedings of the 50th Hawaii International Conference on System Sciences, pp 1267–1276

Mo T, Li W, Chu W, Wu Z (2010) CABS3: context-awareness based smart service system. In: Proceedings of the 6th International Conference on Wireless Communications, Networking and Mobile Computing, pp 1834–1837

Mukudu N, Ventura N, Mwangama J, Elmangoush A, Steinke R, Magedanz T (2016) Prototyping smart city applications over large scale M2M testbed. In: Proceedings of the 2016 IST-Africa Week Conference

Oh JS, Park JS, Kwon JR (2010) Ubiquitous infrastructure and smart service on city gas environments in Korea. In: Proceedings of the 5th International Conference on Future Information Technology

Oliva R, Kallenberg R (2003) Managing the transition from products to services. Int. J Serv Ind Manag 14(2):160–172

Payne AF, Storbacka K, Frow P (2008) Managing the co-creation of value. J Acad Mark Sci 36(1):83–96

Pereira, C., Cardoso, J., Aguiar, A., and Morla, R. (2018) Benchmarking pub/sub IoT middleware platforms for smart services. J Reliab Intell Environ 4(1):25–37

Perera C, Zaslavsky A, Christen P, Georgakopoulos D (2014) Sensing as a service model for smart cities supported by Internet of Things. Trans Emerg Telecommun Technol 25(1):81–93

Priller P, Aldrian A, Ebner T (2014) Case Study: From legacy to connectivity: migrating industrial devices into the world of smart services. In: Proceedings of the 19th IEEE Emerging Technology and Factory Automation

Reiter M, Fettke P, Loos P (2013) Towards a reference model for ecological IT service management. In: Proceedings of the Thirty Fourth International Conference on Information Systems

Ren J, Ma J, Huang R, Jin Q, Chen Z (2014) A management system for cyber individuals and heterogeneous data. In: Proceedings of the 11th IEEE International Conference on Ubiquitous Intelligence and Computing and 11th IEEE International Conference on Autonomic and Trusted Computing and 14th IEEE International Conference on Scalable Computing and Communications and Its Associated Workshops, pp 88–95

Sarnikar S, Deokar AV (2017) A design approach for process-based knowledge management systems. J Knowl Manag 21(4):693–717

Saunila M, Rantala T, Ukko J (2017) Characteristics of customer value creation in digital services. J Serv Sci Res 9(2):239–258

Seeliger R, Krauss C, Wilson A, Zwicklbauer M, Arbanowski S (2015) Towards personalized smart city guide services in future internet environments. In: Proceedings of the 24th International Conference on World Wide Web, pp 563–568

Smirnov AV, Kashevnik AM, Ponomarev AV, Savosin SV (2015) Ontology-based organization of interactions between services in the smart space for hybrid system control. Sci Tech Inf Process 42(5):367–374

Stöhr C, Janssen M, Niemann J, Reich B (2018) Smart services. Procedia Soc Behav Sci 238:192–198

Strüker J, Kerschbaum F (2012) From a barrier to a bridge: data-privacy in deregulated smart grids. In: Proceedings of the 33rd International Conference on Information Systems

Theocharis SA, Tsihrintzis GA (2013) Personalization as a means to improve e-services. In: Proceedings of the 2nd International Conference on Computer, Information and Telecommunication Systems

Tianyong W, Zhengliang X, Gel G (2006) Development and strategy of knowledge management for e-services. In: Proceedings of the International Conference on Service Systems and Service Management

Tien JM (2012) The next industrial revolution: Integrated Services and Goods. J Syst Sci Syst Eng 21(3):257–296

Töytäri P, Turunen T, Klein M, Eloranta V, Biehl S, Rajala R, Hakanen E (2017) Overcoming institutional and capability barriers to smart services. In: Proceedings of the 50th Hawaii International Conference on System Sciences, pp 1642–1651

Vom Brocke J (2007) Design principles for reference modeling: reusing information models by means of aggregation, specialisation, instantiation, and analogy. Ref Model Bus Syst Anal IGI Global, pp 47–76

Vom Brocke J, Simons A, Niehaves B, Reimer K, Plattfaut R, Cleven A (2009) Reconstructing the giant: on the importance of rigour in documenting the literature search process. In: Proceedings of the 17th European Conference on Information Systems, pp 2206–2217

Von Krogh G (1992) Care in knowledge creation. Calif Manag Rev 40(3):133–153

Wang C, Akella R, Ramachandran S, Hinnant D (2011) Knowledge extraction and reuse within "smart" service centers. In: Proceedings of the Annual SRII Global Conference, pp 163–176

Webster J, Watson RT (2002) Analyzing the past to prepare for the future: writing a literature review. MISQ. 26(2):xiii–xxiii

Weijie C, Tong M, Jie C, Yuan W, Jingmin X, Weiping L, Huiping L (2012) A context-aware services development model. In: Proceedings of the International Joint Conference on Service Sciences, pp 194–199

Westwood JA, Cazier JA (2016) Work-life optimization: using big data and analytics to facilitate work-life balance. In: Proceedings of the 49th Hawaii International Conference on System Sciences, pp 1701–1709

Wünderlich NV, von Wangenheim F, Bitner MJ (2012) High tech and high touch: a framework for understanding user attitudes and behaviors related to smart interactive services. J Serv Res 16(1):3–20

Wutzler M, Weissbach M, Springer T (2017) Role-based models for building adaptable collaborative smart service systems. In: Proceedings of the IEEE International Conference on Smart Computing, pp 1–6

Yachir A, Tari K, Amirat Y, Chibani A, Badache N (2009) QoS based framework for ubiquitous robotic services composition. In: Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, pp 2019–2026

Ye F, Qian Y (2017) A security architecture for networked Internet of Things devices. In: Proceedings of the IEEE Global Communications Conference, pp 1–6

Yu C-C (2004) A web-based consumer-oriented intelligent decision support system for personalized e-services. In: Proceedings of the 6th International Conference on Electronic Commerce, pp 429–437

Zhang D, Hu D, Xu Y, Zhang H (2012) A framework for design knowledge management and reuse for product-service systems in construction machinery industry. Comput Ind 63(4):328–337

Zo H (2003) Personalization vs. customization: which is more effective in e-services?. In: Proceedings of the 9th Americas Conference on Information Systems, paper 32

K Realizing availability-oriented business models

Appendix K

Realizing availability-oriented business models in the capital goods industry

Daniel Olivotti, Sonja Dreyer, Patrick Kölsch, Christoph F. Herder, Michael H. Breitner and Jan C. Aurich

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Abstract:
The validation results of a concept for the development of availability-oriented business models are addressed. The developed concept contains five steps by means of primarily design thinking methods. For the validation, the developed concept is applied at Lenze, a German innovative manufacturer of drive and automation solutions for materials handling, handling technology, packaging industry, robotics and automotive industry. Therefore, a use case is defined, business models, extended value networks, persona analyses and customer journey are elaborated. The results show the applicability of the concept for the development of availability-oriented business models for the capital goods industry.

Keywords: Availability,Business models, Capital goods industry, Predictive maintenance, Product-Service-Systems

L Digitalisierung im Einkauf: Eine Referenzarchitektur (DE)

Appendix L

Digitalisierung im Einkauf: Eine Referenzarchitektur zur Veränderung von Organisation und Prozessen

Ines Stoll, Daniel Olivotti and Michael H. Breitner

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Abstract:
Purchasing departments are considered in nearly all companies. On the one hand site changing customer needs and requirements influence purchasing of goods or services. New ways of collaboration in value networks are established. On the other hand digitization and digitalization of the purchasing systems and tools itself are recognized. The following paper aims in identifying critical success factors for the digital transformation of purchasing. Further challenges and chances are elaborated and a references model is created.

Keywords: Digital transformation, Purchasing, Reference architecture

M Assessing Research Projects: A Framework

Appendix M

Assessing Research Projects: A Framework

Jens Passlick, Sonja Dreyer, Daniel Olivotti, Benedikt Lebek and Michael H. Breitner

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Abstract:
Researchers have a lot of opportunities for research in their area. Lot of ideas exists and it is not always clear which ideas should be followed in detail. Therefore a framework for accessing research projects is proposed within this paper. The framework consists of six blocks. Herein the first four blocks help to locate the research ideas. The last block, divided up into five sub-blocks, focus on research design and research approaches.

Keywords: Research framework, Structuring, Research projects