Digital Transformation in the Manufacturing Industry: Technologies and Architectures

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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,

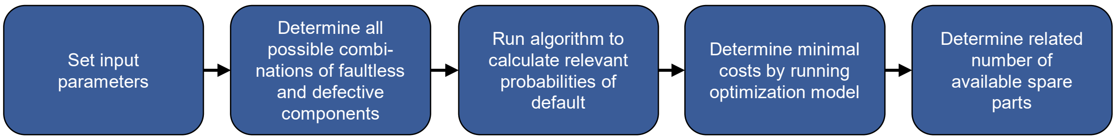

Figure 1: General procedure to determine the optimal number of available spare parts

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.

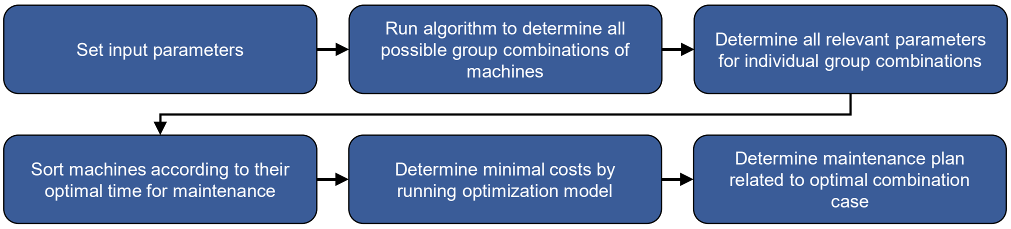

Figure 2: General procedure to determine the optimal maintenance activities

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).

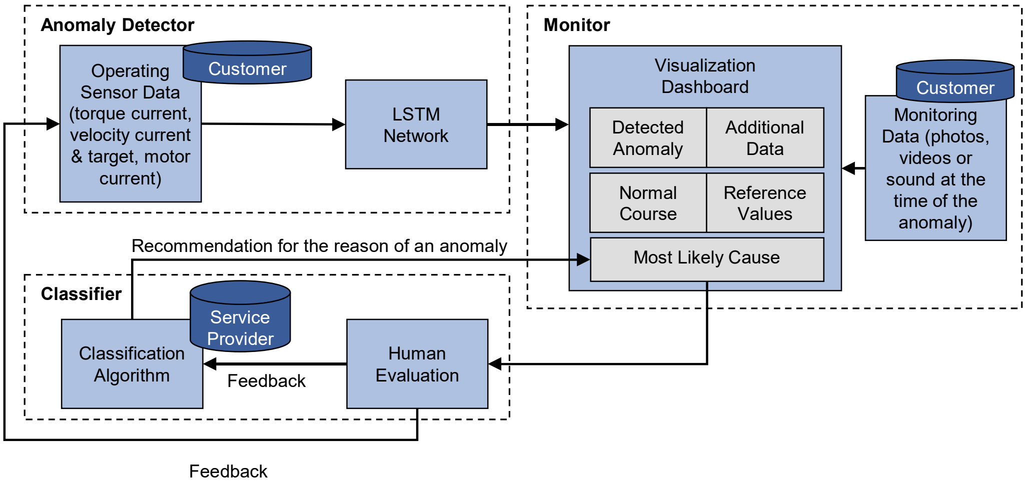

Figure 3: The developed machine monitoring approach

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.

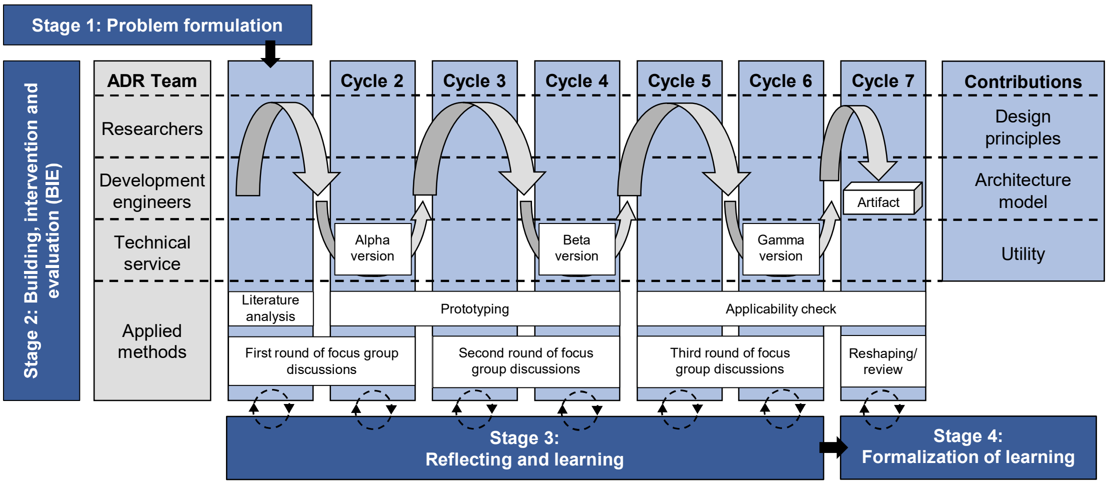

Figure 4: Research design based on the ADR approach from (Sein et al., 2011)

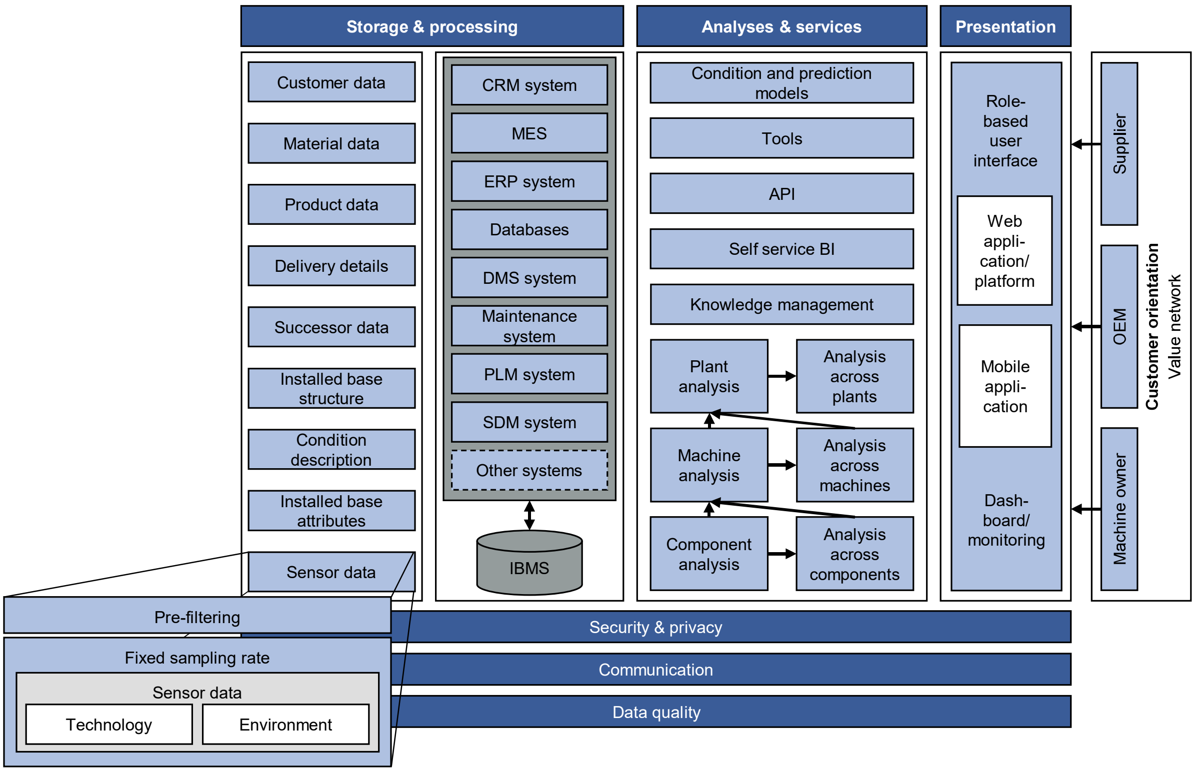

Figure 5: Integrated installed base management system

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.

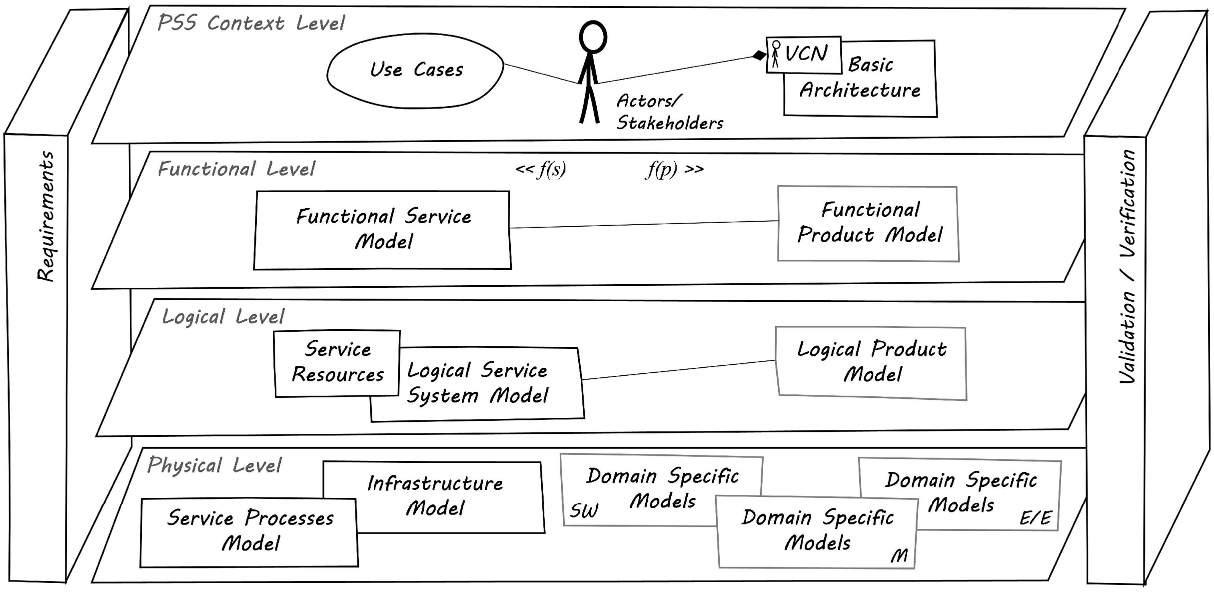

Figure 6: General structure of the integrated PSS modeling framework

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

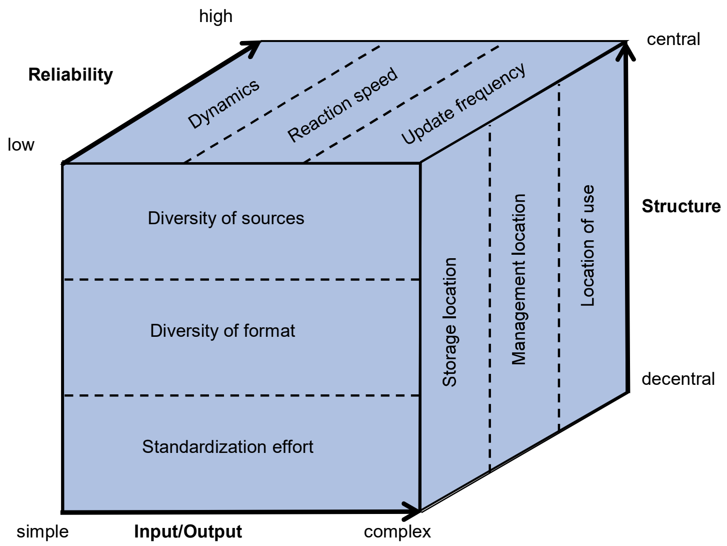

Figure 7: Knowledge management system for smart services reference model

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.

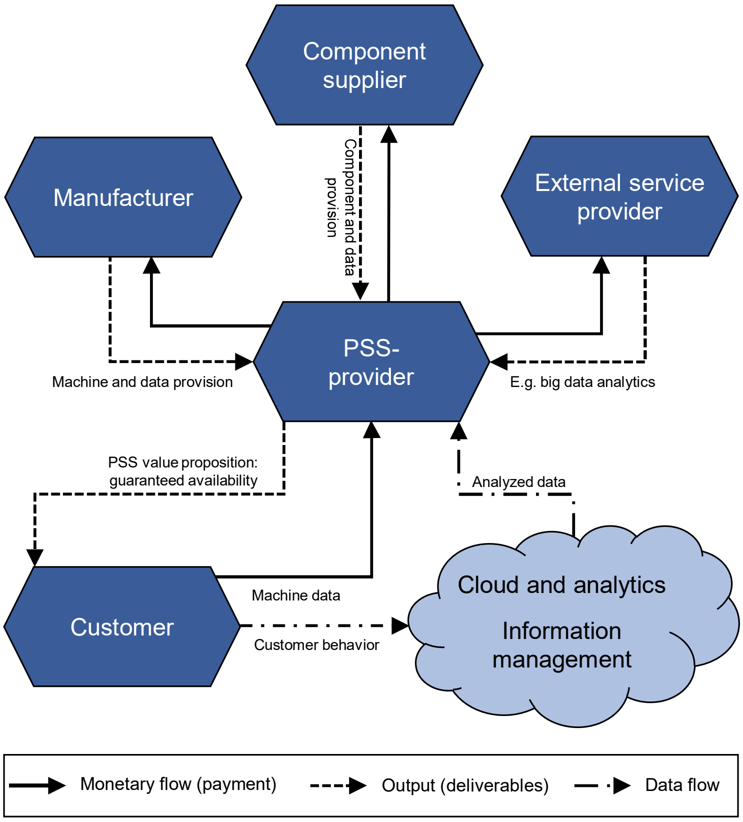

Figure 8: Value network map

Contents