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ORIGINAL ARTICLE

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

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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)

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1 Introduction

In the manufacturing industry, component suppliers and machine builders are shifting their emphasis from solely selling physical products to combining them with services and offering product–service systems (PSS) (Schrödl and Bensch 2013; Oliva and Kallenberg 2003; Neff et al. 2013). Services are an economic guiding force for machine builders and machine component suppliers (Rai and Sambamurthy 2006) because the supply of services for machines and production plants as well as products leads to new sales opportunities and greater customer loyalty (Oliva and Kallenberg 2003; Cohen 2012; Barrett et al. 2015). A more solution-centered view is taken when offering PSS in contrast to offering products solely. Possible services that are combined with products are e.g.: repair and maintenance of machines, spare parts delivery and management and process consulting.

In the manufacturing industry, machinery and equipment are subject to high demands regarding availability and productivity (Haider 2011; Mert et al. 2016). A major challenge for machine builders and machine component suppliers is the fact that they often lack knowledge concerning the state of the deployed machinery and equipment during the use phase (Mert et al. 2016). When offering guaranteed availability and productivity, it is essential to collect and process condition monitoring data (Lin et al. 2006; Fellmann et al. 2011). Condition monitoring data have a high impact when combined with installed base data [i.e. product master data, service data and contractual data (Jalil et al. 2011)]. To date, this has rarely been recognized by researchers. Manufacturing organizations face the problem of how to use existing data from existing IT systems [e.g. enterprise resource planning (ERP) systems, manufacturing execution systems (MES), customer relationship management (CRM) systems] to create a digital copy of machines with the respective installed components, locations, maintenance protocols etc. and how to supplement them with real-time data. This challenge becomes greater when considering a whole value network (e.g. component supplier, machine builder and machine operator). Creating a so-called digital twin based on these data provides the basis for offering individualized services in value networks. Digital twins are realistic models representing machines with all their components, their current state and their interaction with the environment (Rosen et al. 2015; Gabor et al. 2016; Alam and El Saddik 2017). Digital twins can describe physical products and processes as well as services (Kuhn 2017). Information sources for installed base characterization have already been developed by some researchers (Borchers and Karandikar 2006). An integrated installed base management and maintenance system is seen as promising approach (Schröder and Sagadin 2013). An information architecture enabling smart services in the field of installed base management is presented in our previous study (Dreyer et al. 2017). An information architecture represents the conversion of data into meaningful information (Dillon and Turnbull 2005). It includes several steps from the data collection to the presentation of information. Such an architecture permits the storage, processing and analysis of the data, which may then be evaluated to provide a basis for offering services. To the best of our knowledge, researchers did not yet investigate how installed base management is realized in practice. To address this research field, the following research question is proposed:

RQ How can an integrated installed base management system be designed and implemented in the manufacturing industry?

The action design research (ADR) approach (Sein et al. 2011) was adopted as the underlying methodology to answer these research questions. An international engineering and manufacturing company was involved in this process to ensure practical relevance while researchers from a German university focused on academic rigor. Following seven cycles of the ADR process, a continuous interaction between researchers, practitioners and end users was ensured. A demonstration machine was constructed to address the application in practice. To enable a generalization, design principles for the development and implementation of such an integrated installed base management system were created.

The remainder of this article is structured as follows: the ADR approach and its application in this study are dealt with in Sect. 2. The integrated installed base management system, including a literature review of installed base management with a focus on existing architectures and the development process, are presented in Sect. 3. The results obtained by applying general design principles are discussed in Sect. 4. Finally, limitations and conclusions are presented in Sects. 5 and 6.

2 Research design

The aim of this study was to implement an integrated installed base management system in the field of manufacturing. As the basis for a theoretical contribution, design principles for the development and implementation of such an integrated installed base management system were developed. These are not specific to a single company but are applicable to manufacturing companies in general. These contributions are achieved by following the ADR approach by Sein et al. (2011). ADR is an approach which permits the incorporation of action research (AR) and design research (DR) (Sein et al. 2011). The need for this methodology is enhanced by the debate surrounding the gap between organizational relevance and methodological rigor in IS research (Lindgren et al. 2004; Iivari 2007). Two main challenges are addressed by ADR. The research approach aims at solving a problem in an organizational setting by facilitating ongoing interaction between researchers and practitioners. This ensures practical relevance. ADR additionally develops generalized design principles by way of formalized learning from organizational intervention. This aims at contributing to academic rigor. The research process adopted in the conducted study is shown in Fig. 1.

The starting point was that an international engineering and manufacturing company, the target company, required an integrated installed base management system capable of organizing and analyzing the installed base data of the customers (usually

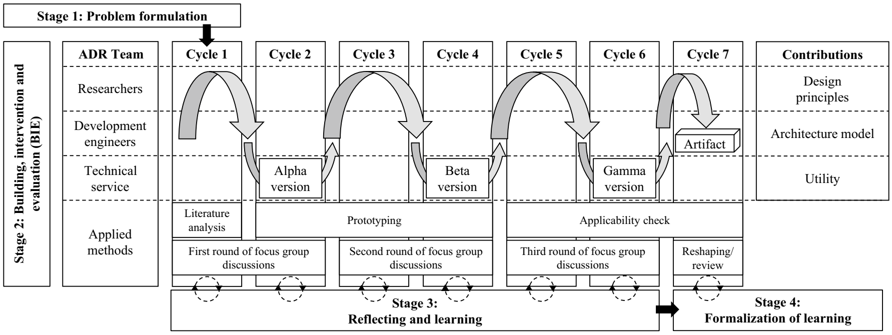

Fig. 1 Research design based on the ADR approach from Sein et al. (2011)

machine owners). On this basis, individualized services in the field of installed base management can be offered to machine builders and machine owners. This was addressed in stage one, namely problem formulation. The specific practical problem was formulated as an instance of a broader class of problems. To address the stakeholders of the ADR process, researches, practitioners and future end users of the developed integrated installed base management system participated in the ADR team formed for this study. The ADR team was made up of researchers from a German university, practitioners from IT department, innovation department, and product service account management and end users from customer service department of the target company. The shared competencies facilitated the problem definition and formulation. The building, intervention and evaluation (BIE) stage is comprised of seven iterative cycles. A prototype for an integrated installed base management system was built and continuously evaluated in the latter based on focus group discussions. In the first cycle of the BIE stage, an initial prototype ("Alpha version") was developed. Requirements identified in the problem formulation stage were implemented in this cycle. An analysis of existing literature and a series of focus group discussions involving practitioners and end users served as input for the integrated installed base management system to be developed. The alpha version was presented to practitioners and end users for evaluation by conducting a further series of focus group discussions in cycle two. Each focus group discussion was documented and evaluated afterwards by the researchers. Based on feedback from cycle two, the prototype was further improved and extended in cycle three ("Beta version"). A second series of focus group discussions started in cycle three and ended with a presentation to practitioners and end users in cycle four. To ensure relevance in practice, an extensive applicability check was performed. Real data from the target company was used in a test run and a test case was defined in cycle five. This test case contained specific services for predictive maintenance based on installed base management. The real-time data test run was applied in cycle five to further enhance the prototype ("Gamma version"). A demonstration machine was built and used for it. Different kinds of data, including sensor data, were used. Feedback and evaluations from practitioners and end users were compiled again in a third round of focus group discussions (cycle six). This feedback was used for an incremental reshaping of the prototype in cycle seven until the final version was achieved. Stage three (reflecting and learning) was carried out simultaneously to the BIE stage to continuously evaluate each prototype version. In stage four, learning from the specific solution was generalized to address a broader class of problems. Hence, the developed design principles and the developed integrated installed base management system aimed at general applicability for different types of manufacturing companies.

3 Integrated installed base management system development

3.1 Problem formulation

In manufacturing, the installed base includes all machines and systems in a production plant. In this study, the "installed base" not only considers the machines as such but every single component of a machine or system, as an extension to the term "asset". Asset management aims at supporting and optimizing the lifecycle of physical assets (Lin et al. 2006). Installed base management extends this objective and considers the interplay between the different components of a machine as well as those of other machines. Inventory management sets off in the same direction and aims at enhancing customer satisfaction by way of optimizing processes (Yang 2008). These processes, however, are not necessarily optimized by considering the interplay between machines and components. The provision of installed base management services is facilitated by product information (Herterich et al. 2015). Installed base management forms the basis for satisfying customer requirements regarding e.g. reaction times and machine availability (Neff et al. 2014).

A project within the target company addressed the requirements resulting from installed base management. To challenge the named demands, the ADR fitted best with the agile project management practiced in the company concerned. The target company, with headquarter in Germany, operates in 60 countries worldwide and its key focus is on automation products and systems. The project focuses on the storage and systematic of structuring the installed base data of machine owners.

The planned services arose during the course of focus group discussions with a machine owner, a German automotive manufacturer. This automotive manufacturer required detailed information on the installed base in their own production plant. Knowledge of the machines and components and their individual conditions should be monitored. The target company aims at offering services to the machine owner to achieve maximal machine availability and output. A portfolio of services based on installed based management was worked out in a focus group discussion. The participants of the focus group discussion were from the departments of maintenance processes, systems technology and automation technology of the automotive manufacturer. Additionally, practitioners from the target company also formed part of the group. These were mainly from the IT, innovation and the services departments. The researchers structured, documented and evaluated the focus group discussion. Predictive maintenance was identified as a suitable example of a service in the field of installed base management. The results are concretized as six key requests:

- Installation errors are reduced or even avoided.
- Error causes and effects are identified immediately and reliably.
- Maintenance efforts are reduced.
- Maintenance schedules are planned optimally based on data.
- It is learned from experience and the knowledge is stored.
- Knowledge is provided understandably at the right time and at the right place.

These six key requests were addressed within an exemplary PSS with a focus on maintenance as well as installed base management. This is well-suited as a contribution to the development of an integrated installed base management system. The main concept was the use of sensor data in combination with installed base data to acquire knowledge about the current condition of machines. The target company as a component supplier has detailed knowledge of the components. The identification (e.g. clear assignment of serial numbers) and structuring of components in the machines was necessary. An intuitive structure of the machines, components and subcomponents was essential. Detailed product information as well as manuals relating to the specific executing tasks of the components should be available (e.g. for a conveyor for package tasks or for a production robot). Sensor data or error data should be assigned to the related component and an error identification and fast troubleshooting should be performed. When an error occurs, the machine operator should be notified immediately via an integrated visualization cockpit. This cockpit provides detailed information for the machine operator about what must be done to solve the problem (e.g. step-by-step guidance). A knowledge database with former errors and performed corrective actions needs to be established to permit case-based reasoning. Analyses of components and machines must be considered in addition to analyses of several machines in chained production. Domain-specific knowledge should be gained and used. Maintenance schedules should be designed with the help of sensor data as well as prediction and optimization models. This contributes to a high availability of machines. The result is that machines are not maintained according to fixed schedules. An integrated installed base management system is necessary to be able to structure, standardize and analyze installed base data. Additionally, processed data, e.g. in form of key performance indicators (KPI) can be displayed.

3.2 Related literature

In keeping with Webster and Watson (2002), a structured literature review to identify relevant literature concerning architectures for installed base management was conducted in the first cycle of ADR. A search was performed in six databases using predefined search terms. The databases included AISeL, IEEExplore, JSTOR, ScienceDirect, SpringerLink as well as Taylor and Francis. Additionally, the meta database Google Scholar was used since practical literature can be found there. The systematic search was performed in English since it is supposed that researchers write in English to reach a broad audience. This also helps to avoid a regional bias. The predefined search terms and the number of hits in the different databases are summarized in Table 1.

Table 1 Number of hits according to search terms and databases

	AISeL	IEEExplore	JSTOR	ScienceDirect	SpringerLink	Taylor & Francis
"Installed base management" AND architecture AND (manufacturing OR industrial)	7	1	0	1	4	0
"Asset management" AND architecture AND (manufacturing OR industrial)	204	38	258	943	1747	441
"Inventory management" AND architecture AND (manufacturing OR industrial)	244	28	160	1164	1528	683
Architecture AND "digital twin"	2	7	1	78	92	5
Architecture AND "digital shadow"	2	1	5	23	64	5

In the first step, articles were filtered out that did not include the development of an architecture. Only publications describing a digital twin in the context of the manufacturing industry were considered. As a result of the whole search process, 18 publications were included in the literature review. These papers were categorized according to nine different topics (Table 2). The topics were not predefined but ascertained during the literature review process. Each paper was reviewed to decide whether the topic was considered. As previously mentioned, the term "installed base management" is not common in the literature. Although this term is not often used in the reviewed publications, the relevant publications match aspects of the installed base definition.

Bagheri et al. (2015) developed an architecture for cyber-physical systems (CPS) that included five levels. A central point in the architecture is advanced analytical methods in interconnected systems that enable self-awareness of machines. All processes from data acquisition to data analysis and value creation were included. Guidelines for the design and deployment of CPS result from their investigation. CPS and digital twins are changing over time and various data is added during the product life-cycle. Jun et al. (2007) took this into account and developed a system architecture for a closed-loop product lifecycle management. In their approach, hardware and software as well as business models were considered. They looked at product lifecycle management (PLM) as a possible approach to increase the performance of business models. The developed system architecture was also applied to a test case for a telecommunication asset management. Marchetta et al. (2011) took a wider approach and dealt with a proactive PLM which serves as a reference framework. Their framework based on three parts: business process model, product information model and an agent-based architecture of applications.

In the manufacturing industry, important data arise during operation phase of machines. MES are typically used for order execution and processing. Schmidt et al. (2011) developed a functional reference model with focus on MES. The aim of the model was to contribute to the standardisation of functions in manufacturing. Communication between the different subsystems deployed for installed base management is addressed in almost all articles. It includes communications between different systems as well as communication through sensors. Communication techniques constitute a major part of CPS (Bagheri et al. 2015; Lee et al. 2015; Gabor et al. 2016). Most modern machines are already equipped with sensors to monitor their current condition (Li and Parlikad 2016). Nevertheless, it is necessary to guarantee flawless communication. Ivezic et al. (2014) emphasized the importance of security, especially regarding the communication infrastructure. The use of data acquisition systems is suggested to link sensor data and further systems, e.g. for analysis and visualization (Demoly and Kiritsis 2012). These sensors and data acquisition systems need to be both developed and carefully used to avoid huge amounts of redundant data (Bagheri et al. 2015; Li and Parlikad 2016; Jun et al. 2007). In this context Gabor et al. (2016) emphasized that data quality needs to be ensured for sensor data as well as simulation data for digital twins.

Data storage and processing are essential to deal with installed base data. Digital twins to manage components and machines are realized using data and information (Bagheri et al. 2015). Modern information and processing tools permit access

Table 2 Literature categorized according to the considered aspects

Author	Data quality	Communi-cations	Security and privacy	Storage and processing	Analyses and services	Presentation	Customer-orientation	Real-time data	Digital twin
Bagheri et al. (2015)		•		•	•	•		•	•
Demoly and Kiritsis (2012)		•		•	•	•		•	
Desta et al. (2014)		•		•		•			
Gabor et al. (2016)	•	•						•	•
Iung et al. (2007)		•		•	•			•	
Ivezic et al. (2014)		•	•	•	•		•		
Jun et al. (2007)		•		•	•			•	
Lee et al. (2015)		•		•	•	•		•	
Li and Parlikad (2016)		•			•			•	
Marchetta et al. (2011)		•							
Schmidt et al. (2011)		•		•	•			•	
Schmidt et al. (2017)		•		•	•			•	
Shih et al. (2012)		•		•	•		•		
Suh et al. (2011)		•		•			•	•	
Wagner et al. (2017)	•	•		•	•		•	•	
Wohlfeld et al. (2017)		•		•	•			•	
Xiang et al. (2018)	•	•	•	•	•			•	
Zhuang et al. (2018)				•	•			•	•

to remote information or to exchange data (Iung et al. 2007; Jun et al. 2007). Different enterprise systems such as ERP systems and MES are used to manage data efficiently (Schmidt et al. 2011). Data and information already collected within these systems can be used and integrated when creating a digital twin. As data as such does not add value, knowledge management is essential to obtain reliable information (Desta et al. 2014). Knowledge management permits an improvement of processes and thus needs to be included in business processes (Desta et al. 2014). The use of analytics in manufacturing is seen as a challenge as well as a great opportunity in the context of services based on installed base management (Lee et al. 2015). Generated information must be retrievable, which is why the presentation of analysis results and generated knowledge to decision-makers is important (Demoly and Kiritsis 2012; Bagheri et al. 2015). Besides supporting a specific application, it is undisputed that an integrated installed base management system must also support the offered services. As services are often an extension to the current portfolio of a company, it must be ensured that new services are integrated into existing business models (Iung et al. 2007). A dynamic adaption of existing services to meet changing customer requirements is equally important (Ivezic et al. 2014).

The previously presented articles provide interesting insights in different aspects of installed base management. But an integrated installed base management system is not presented within a comprehensive approach. Nevertheless, different topics which are valuable for installed base management are already considered. But recommendations and implications for practitioners to use installed base management are still missing. With the help of the developed installed base management system we aim at making contributions both for researchers and practitioners. The integrated installed base management system presented in Sect. 3.4 is mainly based on the performed focus group discussions. No concrete parts of the presented literature could be adopted to design the integrated installed base management system, but the discussed topics served as valuable input for the alpha version. Nevertheless, no explicit model or parts from different models were used as basis for the developed integrated installed base management system. Further, the developed set of design principles aims in helping practitioners to establish an installed management system in practice.

3.3 Requirements of an integrated installed base management system

Based on the problem formulation and the key requests, the requirements of an integrated installed base management system were worked out in a series of focus group discussions. These series of focus group discussions with different employees from the target company were conducted to create an integrated installed base management system that is relevant in practice. The participants were members of the following departments in the company: business process consulting, IT application development, product management, service account management and technical customer service. Within the focus group discussions, three main aspects were subsequently discussed: objective of the integrated installed base management system, general structure and integrated installed base management system design.

Installed base data are aggregated from different sources. Duplication of data should be avoided. This means that existing data should be used and imported as required. Existing data, manually recorded data and sensor data should be brought together in order to create a digital twin. The focus group recommended the creation of a hierarchical structure for structuring machines and components. A structure from general to specific was considered to be suitable to represent a machine and its components.

As the quality of data has been confirmed to be a decisive factor for successful asset management, this is also considered to be a success factor for installed base management (Lin et al. 2006). Common data formats should be used because engineering and manufacturing companies often operate worldwide and data exchange between companies is required. Nevertheless, it is a fact that for some data it is not possible to find a data format suitable to all companies. An example of this is the current condition of a machine. The focus group mentioned that a multiple language support is needed.

Using a central integrated installed base management system avoids isolated solutions. Existing databases can be integrated, or new databases can be implemented. Analyses can be made according to the related service. The possibility of analyzing structured as well as unstructured data (e.g. text data) was mentioned by the participants of the focus group discussions. Furthermore, analyses across different machines and plants are required. Role-based authentication guarantees that data is only viewed or modified by authorized persons.

3.4 Integrated installed base management system design

Figure 2 shows the developed integrated installed base management system. Data storage and processing are described in the first layer. As the data sources in different companies are diverse, it is unclear as to what type of data comes from which system. In the data storage and processing layer, different systems and data collection points are mentioned. Customer data includes information relating to the customer and a history of contacts with the customer. For example, it is important to track contact to customer service in case of machine breakdowns as well as information about sold machines. It is typically organized in a CRM system. Material data includes information concerning a series of products with the same specifications and is usually derived from ERP systems. Not only the structure of a machine or component (bill of material) are important for installed base management but also information about spare parts, sizes and weights. During the engineering process of machines, various data for construction and application is generated. Data generated during the production phase of a component is also taken into consideration. A further data type that is considered is successor data. If components need to be replaced, the component in question may not necessarily be produced anymore and an alternative component must be bought. Orientation on the product lifecycle helps to meet these previous mentioned requirements, PLM systems are used therefore. Several other documents can be processed from document management systems

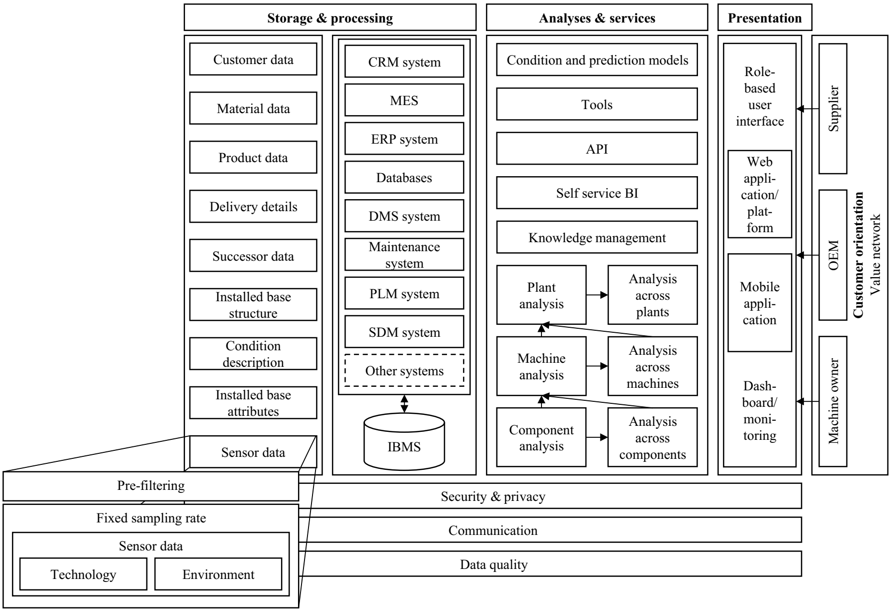

Fig. 2 Integrated installed base management system

(DMS) or the already mentioned systems. It depends on the involved company in which systems documents are stored.

Further, drawings or computer-aided design (CAD) data are important data sources, not only when building up the machine but also for maintenance and repair. A data pool that was discussed intensively by the focus group concerned installed base attributes. This data might be collected in situ by service technicians and includes the installed base structure, a condition description of the whole machine and a description of the individual components. Sensor data is essential for several services and typically stored in sensor data management (SDM) systems. Due to high velocity and volume, pre-filtering and an adequate sampling rate is important when processing sensor data. Sensor data can either be process data which are already retrieved by the machines itself along a production process or received from additional sensors like vibration sensors to detect anomalies for example. For each type of machine, relevant sensor data needs to be defined to see if additional sensor information needs to be included. All data saved in different systems are transferred to an installed base management system database to aggregate and relate the data of a component or machine.

It is important to state out that previously mentioned data is a prerequisite for offering services to customers. We have not linked the data to the systems since it depends strongly on the involved firms and their structures how connections are realized. In general, the main part of data is retrieved by the component supplier or machine builder. Typically, ERP, CRM and PLM systems are involved therefore.

A wide spectrum of different components for machines exists. On the one hand, these are components which are essential for machine operation and can already deliver sensor data or operating data. On the other hand, these are components which are not in focus when considering machine availability and do not provide any data. The machine operator enriches this data with data for the operation of the machine as well as the location in the individual plant. In this case, the ERP system, the MES and the SDM system are the usually involved systems. Several manufacturing companies have also dedicated maintenance systems or use maintenance functions of an ERP system. Further there are systems like DMS or databases which are not specific for a certain partner of the value network and can be used by machine builders, component suppliers as well as machine operators.

Services are considered in the second layer of the integrated installed base management system. The value creation based on the digital twin and the installed base data is addressed. It is necessary to analyze data relating to components, machines and plants with different methods. It is also possible to compare the data across components, machines, or even plants. A knowledge management system is also necessary. A preservation of knowledge can be achieved by correlating actual sensor data with already existing knowledge. The preservation of knowledge can be achieved. For example, if sensor data indicated an anomaly, knowledge is necessary to interpret the data and pass on instructions to the machine operator. Tools such as mathematical models may also be used for analyzing sensor data.

The third layer concerns the presentation of information and services. Several solutions for visualization exist, in the form of mobile or web applications and dashboards. The presentation must fit the individual functions and roles of the partners in the value network. Role-based user interfaces permit the individual definition of read and write permissions. Security and privacy concerns must be considered across all layers of the integrated installed base management system. The same applies for communication and data quality functions.

It should be emphasized that security and privacy are essential to establish such an integrated installed base management system in practice. In the literature, approaches for security of digital twins are rarely described. In contrast, security in the context of the Internet of Things (IoT) and Industrial Internet of Things (IIOT) is widely discussed. Concepts of IoT and IIOT security are adopted to our research topic. Established security and privacy mechanisms for traditional IT systems and enterprises apply as well. Further security and privacy issues arise while connecting more and more machines and represent them virtually in form of a digital twin. Functions to monitor or even control these machines over the internet are becoming more popular with the usage of digital twins. Hassanzadeh et al. (2015) describe six topics for security that should be considered on different levels of IT architectures (device level to enterprise level):

- Monitoring, intrusion detection system (IDS), intrusion prevention system (IPS)
- Firewall, gateway, proxy
- Secure communication
- Authentication, device identity access management (IAM)
- Secure operation
- Vulnerability assessment

The previously mentioned points show that security needs to be considered on different levels (device to enterprise) and with different mechanisms. Pollmann (2017) suggests hardware security modules which are based on blockchain technologies for authentication, code signing of firmware and software updates as well as key injection in hardware chips. In a value network it is necessary to establish security and privacy mechanisms to ensure that data is only shared to authorized partners. For example, manufacturing companies share their raw data of machines with a specific data analysis company and not for all other partners in the value network to perform certain analysis. However, they share the final analysis results to other partners, for example for product improvements. Role-based authentications as well as role-based interfaces should ensure that users only see the content that is relevant for them. Companies see all their own data, but within the company itself regulations based on certain roles can exist. For example, maintenance stuff can only see data from machines that are relevant for them. Various technical authentication methods exist which need to be modelled in a separate systems architecture. They strongly depend on the individual roles and partners in a value network as well as on the confidential level of the exchanged data. One example of an approach for access control in semantic data federations is presented by Fabian et al. (2012). Herein an architecture for cross-company data exchange is presented. Due to the heterogeneity we do not provide specific solutions of mechanism in this article.

The particular value network is also an important aspect to consider for the integrated installed base management system. It has significant influence on the elements considered and how they are fulfilled. Based on the value network different data sources are addressed and provided by different partners. Also, the offering of services and analysis is value network individual. Machine builders as well as component suppliers can offer similar services to customers.

3.5 Applicability check based on a test case

The applicability check refers to the fifth to the seventh cycle of ADR. An applicability check is essential to ensure relevance for practitioners (Rosemann and Vessey 2008). The integrated installed base management system was implemented in the field. It was evaluated in a test run within the target company.

A comprehensive test case dealing with predictive maintenance as a representative service was developed in a third series of focus group discussions. Experts from the innovation, IT service and demand management departments as well as from the service account management department were involved. The maintenance services include the following functions, which should be supported by the integrated installed base management system:

- Representation of machine topology
- Provision of individual documentation
- Provision of actual and past maintenance information
- Creation of maintenance schedules
- Condition-based maintenance

- Process of sensor data
- Inclusion of predictive maintenance models and algorithms
- Initiation of service requests
- Alarm signals and notifications
- Spare parts management and ordering
- Enabling of remote VPN connections
- Visualization and dashboards/KPI

A physical demonstration machine was constructed containing several applications and components that were required to realize the test case. As the company is an automation specialist, the demonstration machine consists of hoist and conveyor applications for automated goods transportation. Figure 3 shows a schematic drawing of the demonstration machine.

Several machine axes were included to permit a continuous material flow of goods. To realize this, a total of seven geared motors and inverters were installed. The left hoist axis [A] was equipped with a conveyor [B] to transfer goods on different vertical levels. The same was realized on the right-hand side with the geared motors [F] and [G]. In the center of the machine three conveyors were arranged one above the other to transfer goods from one side to the other side. The geared motor [C] drives the highest conveyor belt. The other two motion axes in the center of the demonstration machine are powered by electrically-geared motors [D] and [E] with an included inverter on top. All other motion axes are powered by a geared motor with separated inverters. Three goods of about 10 kg each are moved simultaneously for demonstration in the machine. A schematic model of how the demonstration machine was realized and embedded in its environment is shown in Fig. 4. A programmable logic controller (PLC) manages the movement and coordination of the different axes in the machine. The PLC also transfers sensor data to an industrial PC, where data is pre-processed. An additional bearing sensor transfers data via

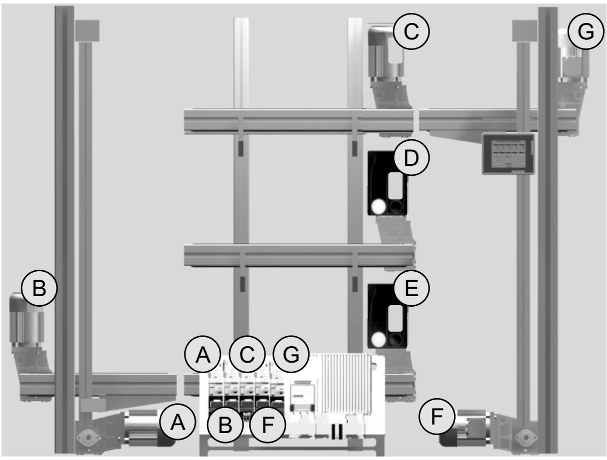

Fig. 3 Schematic drawing of the demonstration machine

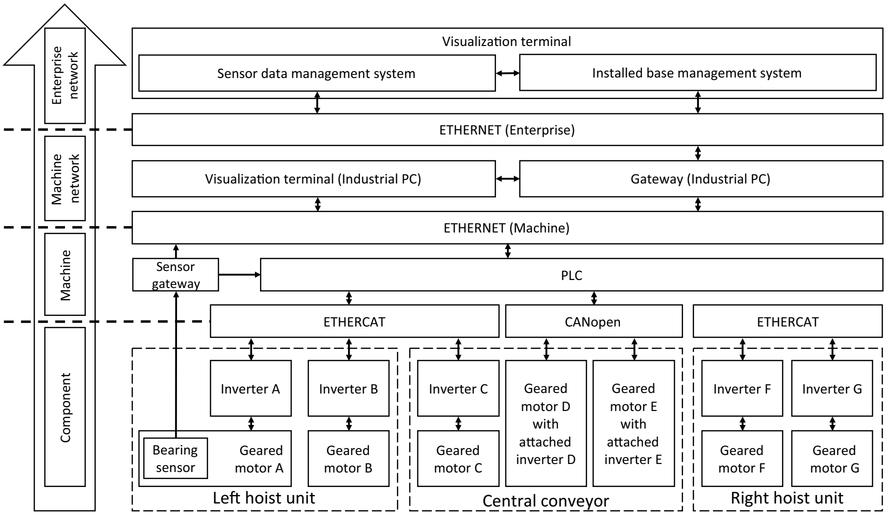

Fig. 4 Schematic model of the demonstration machine

an external sensor gateway to the industrial PC. From this point, the data is transferred to a sensor data management system. A visualization terminal included in the machine allows the machine operator to monitor important parameters. It was realized via a web tool. The demonstration machine was not only used to process sensor data but also to transfer data to the integrated installed base management system. Machine topology, including all components and the hierarchical structure of all parts, is necessary for installed base management. This is also a basic functionality for other functions and is visible to users.

The database for the demonstration machine in the test case was hierarchically structured. To be able to demonstrate the used structure, it was described with the help of a class diagram based on the unified modeling language (UML) building on the architecture. UML enables to display hierarchical structures between classes through associations. We have used associations in the test case to reduce complexity and ensure general applicability. This feature is used to illustrate the structure of the machine, as required by the focus group. As the number of hierarchy levels is not limited, it is possible to create classes of subcomponents by way of inheritance. An attribute specifies a class through parameters. For example, a machine is described through type, manufacturer, producing country and year of construction. Additionally, operating data are connected to a machine. It is possible to associate a class with the next highest class or to remove an existing association. It is also possible to import data from other data sources. If the attribute values are not imported from external sources, the attributes can be entered and updated. This can be achieved by getter and setter methods. The methods are not displayed for each attribute that can be adopted. Instead, the get() and set() methods are described generally. Figure 5 provides a detailed insight into the structure of the demonstration machine data. For reasons of clarity attributes are not named in the figure.

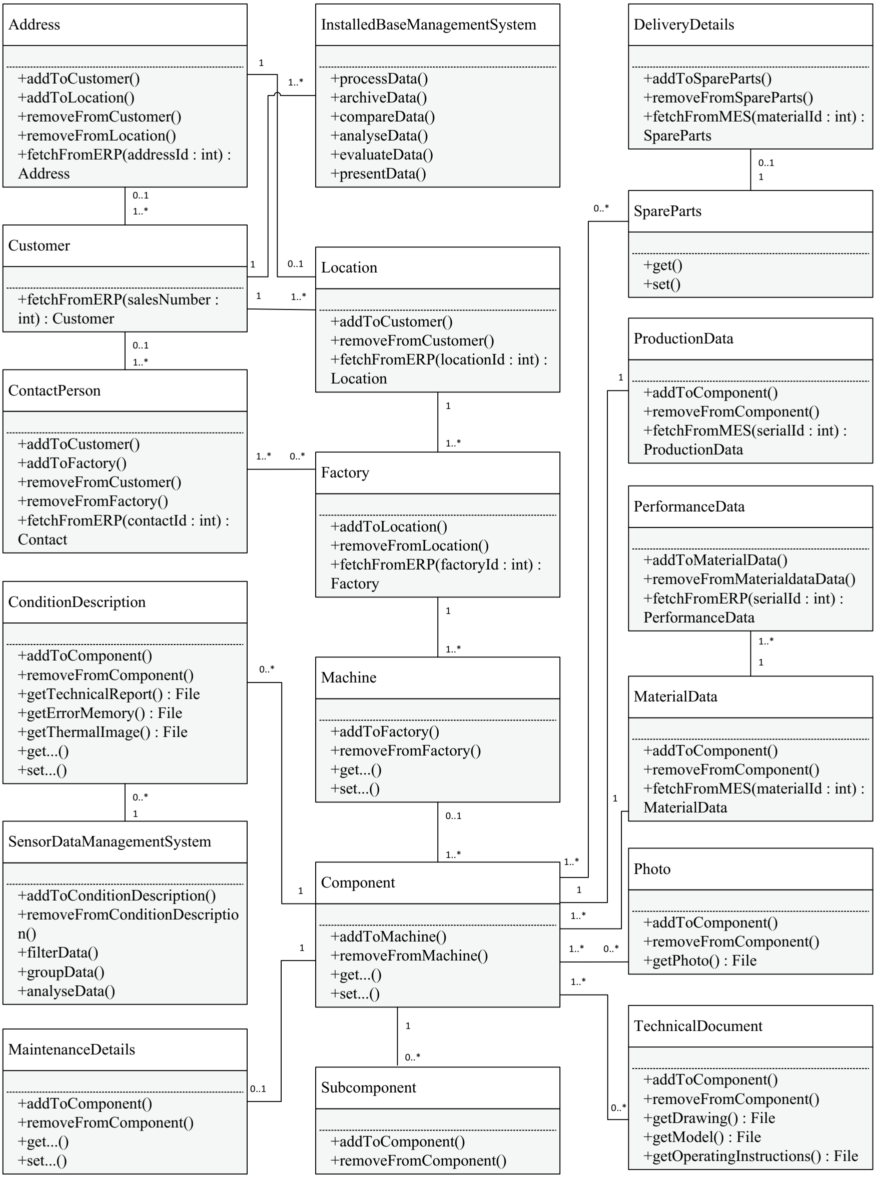

Fig. 5 Class diagram applied to the test case

In the test case it was possible to partially import data and complement these with manually-entered data. It was appreciated by the focus group that existing data from other databases can be added to a component, e.g. information on production that is already stored in a system. This was also realized within the test case. As a large amount of data is collected and transferred, a reliable connection between the different systems is required. Sensor data are filtered, grouped and analyzed in a sensor data management system. As sensor data cannot be processed in ERP systems or MES, a further system was added to handle sensor data. It was possible to integrate external analysis tools as required by the focus group. The selected structure permits the storage of all data and information collected during the test case investigation and thus to create a digital twin. The integrated installed base management system is the highest unit of the structure. The system processes and archives data and analyzes and evaluates the data and information generated.

Several functions of the test case contribute to the maintenance of machines. Maintenance information are stored, and maintenance schedules are provided. These maintenance schedules are either static from manuals or instructions, or dynamic, based on sensor data and condition monitoring. Sensor data are essential in the test case for offering services. The current condition of components and the machine in general is provided for intelligent maintenance schedules. Predictive maintenance models and algorithms for various components are used in the test case to achieve this. Predictive maintenance also triggers actions such as alarm signals and notifications or even the automated ordering of spare parts. A comprehensive spare parts management system is required that also includes detailed information concerning delivery times.

The experts emphasized the importance of suitable interfaces. A role-based visualization for the service provider, machine owner and machine operator was provided, containing important KPI as well as machine and maintenance data. Sensor data were displayed in real-time and can be observed directly at the machine on the industrial PC. Additionally, it was possible to observe sensor data and further indicators via a secure virtual private network (VPN) connection to the machine. Machine operators can send service requests when support is needed. Furthermore, alarm and notification functions were implemented, including automated service request triggering. Support can also be realized via VPN.

A point worth mentioning is that the developed integrated installed base management system is generic and usable for very different kinds of services. As indicated by the test case, it is also applicable to concrete services and real data collected in the field. Regarding the seventh cycle of ADR, aspects emphasized by the focus group were taken up and considered when optimizing the integrated installed base management system. The fact that the test case shows practical relevance of the architecture means that it contributes towards the simplified creation of a digital twin aimed at offering individualized services.

4 Formalization of learning and discussion of results

Following the ADR approach, an artifact was created that is relevant in practice. An integrated installed base management system was developed which passes all seven cycles of the presented ADR process. Several focus group discussions and a test run in a target company were conducted to ensure practical relevance. For the test run, a demonstration machine was built, and incoming data were structured according to the developed installed base management architecture. Through formalization, the learning process was converted into general design principles to contribute to academic knowledge in this research field (Table 3). Examples as well as standards and best practices were identified for each design principle. Risks and opportunities were discussed to illustrate the design principles.

The project group named transparency as essential for installed base management. A clear structure of the digital twin of machines and components must be provided. The more company-specific classifications are implemented the higher is the reduction in transparency. In the presented test case, each component had an individual serial number. By means of a serial number, a specific manual can be retrieved, or spare parts can be provided, e.g. in case of an error. An unequivocal name has the advantage that each component can be uniquely identified. This is not only an important aspect for the presented test case but generally necessary for an installed base management. A unique ID number or identifier for each component also ensures clear assignment and identification. Transparency also helps to evaluate data quality, which is a basis for a reliable analysis and thus a critical success factor.

Besides transparency, standards should be used when designing an installed base management. Standardization helps to reduce the effort regarding individual customization. Considering the presented test case, ETHERCAT, CANopen und ETHERNET were used as the underlying communication protocols. A defined data format had to be used for a specific type of data. Otherwise, smooth operation of the system could not be guaranteed. Data should not only be analyzable by experts, but data handling should also be automated with the aid of tools. Therefore, machine readability of the data is a perquisite (e.g. XML files). In the demonstration machine, the data type was predefined to permit automated analyses using e.g. prediction models. Standards were not only necessary in the test case but are generally recommended because installed base management involves different partners of a value network. However, an agreement on standards is a challenging process. Different standards based on domain, region or individual strategies are often used. Predefining the standards that should be used contributes to a better workflow. Openness for different standards should be considered in order to adapt to, e.g. partners in the value network. The agreement on standards that are used simplifies the cooperation.

The data structure as well as the generated information do not only have to be understood by employees of only one department or a single plant but throughout multiple departments. It is assumed that employees from different departments and countries or cultures have another view on the data structure. This requires internationally valid regulations to avoid the risk of misinterpretations. This is enhanced when companies interact continuously in worldwide value networks. One example is multilingualism. This was implemented in the demonstration machine. It was required that information can be maintained both in English and German. Looking from a more universal perspective, not only these two languages should be supported but different languages in general. Therefore, internationality should always be considered when designing an installed base management.

A role-based authentication guarantees that data privacy is complied with. Security is important, especially because sensitive company information or sensor data are processed, and unauthorized access must be prevented. In the demonstration machine, security concerns were addressed by means of tunnel services, e.g. VPN.

Table 3 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 and 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 and 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)

Table 3 (continued)

Design principle	Description	Examples	Standards/best practices
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, KPI, 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)

Security mechanisms that go beyond an access involving only a login and password contribute to user's trust. Data should be encrypted before transmitting it. In the developed integrated installed base management system, security and privacy concerns are depicted as an interdisciplinary aspect of the previously-mentioned layers and functions.

Real-time data serves as a valuable data source for installed base management services. This kind of data needs to be pre-processed on the machine level and only relevant data should be passed on. Otherwise, a flood of data occurs, and network bandwidth is reduced. Data that only changes slightly, in the test case for example the operating hours of components, have a lower sampling rate than e.g. data representing the torque value. Therefore, the sampling rates were different in the test case. This should be supported by the underlying infrastructure. Different approaches exist for processing sensor data in the data analysis process. In the demonstration machine, different fieldbus networks were used to transfer the sensor data of the different components. It should be ensured that communication with the controller is not disturbed when retrieving sensor data. For this reason, suitable cycle times for sensor data were defined. Machine data were transmitted in the demonstration model via OPC unified architecture (OPC UA). This protocol has the advantage that the data is not only transmitted but also described semantically. Interfaces to enterprise systems permit the combination of real-time data with enterprise data from systems such as ERP and CRM. Systems in present-day use may be changed, extended or aggregated, e.g. demarcations between ERP and MES can blur. This requires flexibility regarding the interfaces. Programming in the form of function blocks may provide the necessary flexibility. In the test case, a cloud platform was used to store and subsequently process data. In general, cloud platforms for analysis or for the provision of services also require interfaces or application programming interfaces (API). Interfaces in the whole chain from data generation and collection to transmission to the front end must be planned and specified.

Connected to the infrastructure, the installed base management database should be scalable. In the case of the demonstration machine, the number of components was fix during the test. But when implementing an installed base management in the field, it is not necessarily known, how many components, machines or even plants will participate. Therefore, it is required that more data sources do not pose a problem. The sampling rates of some sensor data were adapted during the test run of the demonstration machine. Although the data stream has not been increased greatly, more space was needed in the cloud where the data was processed. The more components form part of the installed base management, the higher are the effects when the sampling rates increase. This must be intercepted by the system.

Prediction models were implemented in the demonstration machine. With the aid of sensor data, it was possible to determine, e.g. the remaining life expectancy of a gear. A combination of sensor data, i.e. torque and rotational speed, with data about the material components were required since specific power and construction data serves as input for the model. Additionally, data of the physical application of a component serves as input for the lifetime models. The models where created in several complex test cases where the deterioration of different gearboxes was observed. Physical tests were used to give a possible maximum life expectancy (machine hours) based on a specified application for customers and a high safety level is integrated to ensure the guaranteed availability. Based on sensor data the current condition of components can be integrated in the mathematical models whereby much more precise information of the real deterioration is given to prevent breakdowns. Different mechanical strains of the components are due to the individual application. This needs to be considered by the prediction models.

Sensor data analysis and evaluation of the collected data across components, machines and plants were enabled through the service layer of the integrated installed base management system. Sensor data or analysis results, maybe enriched by further data, can be used to continually adapt existing algorithms or models that describe processes. When the respective functions are provided, the customers are enabled to improve their production processes. Sensor data can be used to determine an imminent machine breakdown before the breakdown really occurs. This enables to adapt the production processes in a timely manner, ensuring a continual and interruption-free production. The same occurs with planning of maintenance schedules based on the individual condition of a component. This also may be realized by machine builders or component suppliers as a service. A decision support system (DSS) based on an optimization model can be used to determine the optimal maintenance policy for machines in a production site (Olivotti et al. 2018a). Herein the current condition of a machine, retrieved by sensor data, is considered and the breakdown possibility is determined. Furthermore, not only machine individual maintenance activities are considered, but machines can be grouped and maintained on the overall best maintenance point in time to save maintenance costs and downtimes. Component suppliers faces the problem that their components are installed in different machines and applications. Therefore, it is difficult to use specific models to predict the actual condition of components due to very different application scenarios of the components. For this case an approach was developed which combines machine learning and domain experience (Olivotti et al. 2018b). Neural networks are used to determine an abnormality of an industrial component or machine. In another step the cause of the error is determined by domain experts. By the combination of these two aspects the root causes can be trained and used in the future to e.g. guide machine operators through a repair process.

As it is not possible to structure all data, e.g. free texts written by employees in the field, semantic analyses are necessary. A challenge is to include domain knowledge and knowledge management. Knowledge management also includes unstructured data. Knowledge management supports learning from past successes and failures (Mouna and Dakhli 2016) and encourages continuous learning, e.g. prediction models can be optimized. In the case of the demonstration machine, there was only data from one machine that could be analyzed. But expert emphasized that the possibility to compare analysis results across different machines with the same functions helps to optimize processes. Even more general, comparing machines not only in one plant but across plants, does even provide more potential regarding process improvements.

The offered services that are realized based on the integrated installed base management system must be in accordance with the company's strategy and product portfolio. An integration into already existing processes and business models is indispensable and challenging. One important aspect is the cost structure. Before offering a service related to installed base management, it must be decided how the service will be accounted (Kennedy and Keskin 2016). It is possible to sell the inclusion of each machine into an integrated installed base management system. Another possibility is to determine a fixed price per month, independent from the number of new machines included. Depending on the specific industry, the customer and further circumstances, the optimum pricing strategy varies. It would also be possible to sell the services that are realized in the demonstration machine in combination with products, i.e. PSS. However, many different scenarios are imaginable. From a supplier's or a machine builder's perspective, installed base management enables to identify the machine owner's needs in the short and medium term. Direct contact with the machine owner can result in further sales and customer satisfaction as well as increased loyalty.

Different technologies and tools can be used for visualization (e.g. HTML sites, Java applications). The demonstration machine was equipped with a visualization terminal attached to the machine to display status and error information for the machine operator. A second visualization is realized in a prototype for maintenance or service personnel responsible for monitoring several machines. An individualized user interface has the advantage that only information is displayed that is relevant to them. The integrated installed base management system needs to be flexible to support a wide range of services and tools. Different data visualizations for each partner of the value network need to be provided. Machine owners are primarily interested in monitoring their own machines and plants. The interaction between different machines and their interplay in chained production is essential. This can include information concerning the current status of production to maintain high machine availability. In contrast, machine builders pay attention to their machines located in various plants of several customers. They can offer support when machines are not working properly and compare machines to make continuous improvements. As a further view, component suppliers pay attention to their own products located in various machines, which is relevant to product improvements and upcoming products. The necessary visualizations must be determined for the specific installed base management. As the test case includes a machine with several components, a visualization was realized to compare similar components graphically. In case of more machines, it would also be possible to do so for components installed in different machines. Depending on the partners of the value network, the sensible visualization views vary. Nevertheless, it should be taken into account that different partners are interested in diverging information and analysis results.

Installed base management is realized within a value network. As already mentioned, considering the value network is essential. On the one hand, the output is used in different ways by the partners. This is comprehensible when thinking about the described different views within the visualization. On the other hand, the input is not generated by only one partner. For example, providers of components have more detailed information about their products than the machine builder has. In turn, the machine builder knows how the different components interact. Finally, the machine user generates sensor data while manufacturing. If not all partners are integrated, the risk of incomplete digital twins arises. Within the test case, the target company represented all three described partners. Nevertheless, it is imaginable that the aggregation of the information of the different partners is necessary to realize a digital twin.

5 Limitations and further research

The created integrated installed base management system provides the opportunity to manage installed base data. However, certain limitations must be considered. The integrated installed base management system was developed within a project of an engineering and manufacturing company. The fact that the requirements were worked out in focus group discussions with the target company and an automotive supplier means that there is no guarantee that the requirements are practicable for other companies. Nevertheless, the researchers aimed for general applicability within the ADR process. Installed base data collected in a test case involving the use of a demonstration machine of the target company formed the basis for defining the necessary data types. Different partners in the value network must be taken into account when discussing a reliable integrated installed base management system. In the presented project, the focus is on a component supplier and its requirements. Requests by a machine owner were also considered. As a machine builder did not form a part of the focus group discussions, an adaptation of the architecture for these kinds of partners cannot be ruled out. The requirements of other partners in the value network should be focused on in further research.

As the architecture was developed and tested in the company headquarters in Germany, it is not certain whether a transfer to other languages is possible without a great deal of effort. The data were mainly stored and structured in German and a transferal to other languages was not necessary in the test run. Nevertheless, the test case shows that the integrated installed base management system provides the opportunity to unite and standardize different data types. The test case focused on functionalities that are necessary for predictive maintenance. As services cover a very wide field, a broad range of services is conceivable for manufacturing. It cannot be excluded that the integrated installed base management system must be adapted or extended to meet the requirements for other services. In this context, evaluating the flexibility and extensibility of the integrated installed base management system is a possible approach for further research. The demonstration machine already included several applications and components. Testing the integrated installed base management system not only for a single machine but for a whole plant or even several plants may lead to further findings. It is therefore suggested to perform a test on a real production site with a large number of machines and components. An evaluation with other data may also lead to further enhancements. It would be interesting to evaluate the integrated installed base management system and the developed design principles in focus group discussions with value network partners not yet included in the focus group.

6 Conclusions

Nowadays, manufacturing companies are not only interested in selling physical products but also PSS to gain competitive advantages and open up new revenue channels. To support this shift in emphasis, an integrated installed base management system was presented in this study for the purpose of offering services in the manufacturing industry. Following an action design research (ADR) approach, a continuous interaction between practitioners from an engineering and manufacturing company and researchers was established. Requirements for an integrated installed base management system were drafted in several focus group discussions and extracted from literature. An example of a portfolio of services in the context of predictive maintenance was established. A test case was specified and a test run using a demonstration machine was performed to demonstrate the applicability of the integrated installed base management system in practice. With the help of the applicability we aim at showing how such an integrated installed base management system can be implemented in practice. In order to generalize the results, design principles for the development and implementation of such an integrated installed base management system were proposed.

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