Comprehensive View on Architectural Requirements for Maintenance Information Systems

Andreas Reidt[1], Stefan Schuhbäck[1] and Helmut Krcmar[2]
[1]fortiss GmbH, Guerickestraße 25, Munich, Germany
[2]Chair for Information Systems, Technical University of Munich, Munich, Germany

Keywords: Maintenance Information System, Digitization, Industry 4.0, Industrial Internet, Software Architecture, Mobile Support System, Predictive Maintenance, Condition Monitoring, Requirement Engineering, Technical Customer Service.

Abstract: Concepts of Industry 4.0 and digitization are leading to a much higher complexity of production facilities, related processes, and activities such as maintenance. As a result, the demands made on the process of maintenance and the maintenance workers involved are getting more demanding. To meet these requirements, many information systems have been developed with different purposes and technologies. Yet the development of these systems is occurring in isolation and the main challenges of the integration of these maintenance solutions and their information with each other are not addressed. The resulting solutions and their architectures lack a sustainable holistic viewpoint from the start. To solve these challenges and to give developers a framework in which to develop information systems for maintenance, a holistic view of the architectural and requirements is needed. Therefore, a framework for the general requirements of all maintenance information systems has been developed in this paper. To achieve this, a literature review was conducted where the requirements for a broad set of maintenance information systems were gathered and compared with each other. Based on this information, general principles for the architectures of maintenance information systems were derived.

1 INTRODUCTION

Progressive digitization is not only leading to completely new enterprises, but also poses major challenges for traditional, established companies as they are also subject to fundamental change (Horváth, 2017). Trends and technologies like IoT (Gubbi et al., 2013), CPS (Lee, Bagheri and Kao, 2015), Industry 4.0 (Lasi et al., 2014), and respectively the Industrial internet (Lin et al., 2015) are driving this change to lead to major challenges, especially for manufacturing companies.

On the one hand, the existing processes are subject to a strong and purely technological change. On the other, changes to the company's current business models are not only made possible by current technologies but they are also necessary, so that companies must prepare for a disruptive change (Reidt, Duchon and Krcmar, 2017). Producing companies often turn into producing service providers (Daeuble et al., 2015).

Linked to these changes are processes such as maintenance for production plants, which struggle to cope with this new resulting environment. This introduces additional complexities such as changes to the business models, more complex machinery throughout the maintenance industry and higher requirements for the maintenance workforce.

To compensate for these effects, a large variety of information systems (ISs) exist within the industry to support maintenance operations and tasks. Besides such traditional systems as Computerized Maintenance Management Systems (CMMS) (Gabbar et al., 2003) that are becoming enhanced with additional features, completely new support systems with state-of-the-art technologies such as mobile support systems (Fellmann et al., 2013), or systems that use augmented reality (Zhu, Ong and Nee, 2014) are being introduced to the industry.

The main issue with the current development is that existing systems have been developed and are being operated in an isolated manner, and that they form isolated data islands (Galar, 2014). The

Reidt, A., Schuhbäck, S. and Krcmar, H.
Comprehensive View on Architectural Requirements for Maintenance Information Systems.
DOI: 10.5220/0006698602490257
In *Proceedings of the 13th International Conference on Evaluation of Novel Approaches to Software Engineering (ENASE 2018)*, pages 249-257
ISBN: 978-989-758-300-1

information exchange between systems is scarce and if present often complicated or not completely automated. This is reinforced because many of these systems have a specific use case, which is implemented in isolation from the Big Picture that current maintenance operation needs. Moreover, existing systems and requirements for holistic maintenance systems are not known and their development is costly. Furthermore, such a development requires an interdisciplinary view, which combines knowledge from various fields such as computer science, maintenance, business and industrial automation.
To approach these challenges an architectural requirement framework is proposed in this paper that emphasizes requirements for maintenance ISs. The framework will show requirements within different ISs and pin-point similar and holistic requirements that must be considered in the development process of software architectures for maintenance related IS. Furthermore, relevant ISs in a production environment and support systems for maintenance are presented that can fulfil these requirements or their integration are needed in order to extract relevant information.

Together, the systems and the holistic requirements form the cornerstone for a framework that can be the basis for the development of sustainable and holistic software architectures for maintenance ISs.

In the following chapter, the existing IS for production which have a supporting role to maintenance activities as well as dedicated IS with the sole purposes to aid maintenance activities on all levels are presented. Chapter 3 describes the used method of identifying requirements of ISs and the subsequent clustering. Lastly, a framework is generated and the corresponding outcome is discussed. Furthermore, research outlooks in the context of creating additional reference architectures for maintenance ISs are presented.

2 IS FOR MAINTENANCE

The classification of the most relevant ISs for maintenance requires a definition of the framework for the concept of maintenance. In this paper, the concept of maintenance can be understood as 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" (Deutsches Institut für Normung, 2015).

Maintenance, however, comes in a variety of types, concepts and strategies, which have been developed over the last few decades. These influence the selection and characteristics of maintenance systems. Therefore, concepts, types and maintenance strategies relevant to the information systems are presented below. Subsequently, ISs are described, from which information is needed in order to carry out maintenance tasks. These systems form the core of the IT architecture for most manufacturing companies. Then, an overview of current systems that are designed to support maintenance and their terms in literature and practice is provided.

2.1 Maintenance Types, Concepts and Definitions

Apart from different maintenance measures, the literature distinguishes maintenance strategies or types and concepts. The two main strategies or types according to Niu et al. (2010) are reactive and preventive maintenance. Reactive maintenance describes actions after a unit failure occurs whereas preventive measures are taken beforehand to mitigate failures. The preventive measures can be divided into subcategories: periodical and condition based maintenance.

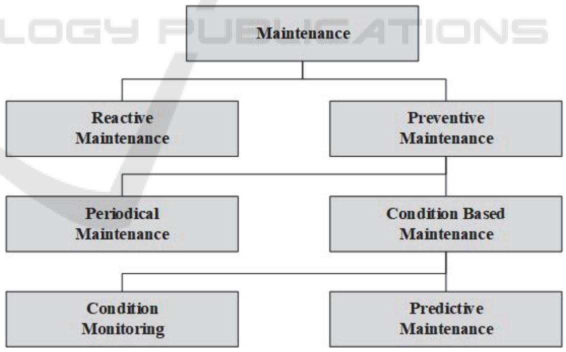

Figure 1: Maintenance strategies based on Niu et al. (2010).

With periodical maintenance, tasks are planned with fixed intervals, regardless of the current state of the machine. The intervals can be time-driven or based on other variables such as mileage.

The condition-based approach will schedule maintenance measures based on the current condition or on a predicted future condition calculated, based on statistical models and data mining. This distinction between predictive maintenance and condition monitoring is essential in order to distinguish newer

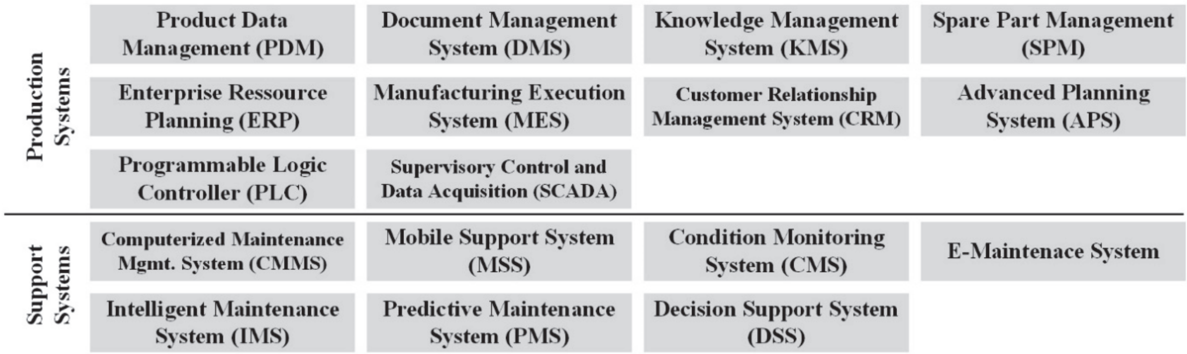

Figure 2: Overview of relevant systems for maintenance, divided into production systems and support systems.

ISs for maintenance. The entire representation of the subdivision of maintenance strategies or types is shown in Figure 1. Within manufacturing industry, all approaches mentioned are used to some degree and introduce specific requirements for supporting IS. Reactive maintenance will require the IS to assist with failure analysis and repair whereas preventive maintenance requires planning and scheduling of maintenance tasks, according to the current or future state of the machine.

These concepts and types have a significant impact on the required features of maintenance ISs and the necessary information a maintenance worker has to extract.

2.2 Production Systems

In industrial applications, maintenance information is needed from a variety of ISs to efficiently perform maintenance tasks. These ISs supply production and maintenance with information and they are located at different levels of the automation pyramid (Bauernhansl, 2014). In the upper section of Figure 2, a list of the identified most popular ISs relating to maintenance tasks is presented.

Product Data Management (PDM) systems manage the data used within the development process and provide access to this data across every phase of the product lifecycle. Connected with these kind of systems are Document Management Systems (DMSs) which are often used to manage physical and/or digital heterogeneous documents within companies. Both systems can be seen as parts of a generic Knowledge Management Systems (KMSs) enable the gathering and display of context-dependent, explicit and implicit knowledge or information of an organization (Maier, 2007).

Spare Part Management (SPM) systems contain information on spare parts, including pictorial representations, 3D models and information on bills of materials (BOMs).

Enterprise Resource Planning (ERP) systems support all business processes while Manufacturing Execution Systems (MESs) are tailored to technical production processes.

Customer Relationship Management (CRM) systems are closely connected to ERP systems with the goal of increasing shareholder value by managing customer data and steering business processes to good customer relationships.

Advanced Planning Systems (APSs) are used to manage material, personnel, tooling and production plants across national borders. Many tasks within APSs can be found in part in the systems described above. The focus of APSs is mainly on the mathematical optimization of these complex problems.

Programmable Logic Controllers (PLCs) directly control the production process on the lower level of the automation pyramid within a machine or group of machines. The real-time data generated is used within Supervisory Control and Data Acquisition (SCADA) systems to directly manage the production process. PLC and SCADA systems contain important information for real-time condition monitoring.

2.3 Support Systems

In contrast to the ISs mentioned in the previous section, the following ISs have been identified as systems dedicated to supporting maintenance activities directly rather than just serving as an information source. The ISs are presented in the lower section of Figure 2.

CMMSs are among the first systems used to support maintenance tasks. CMMSs are used to provide support mainly in maintenance planning and controlling tasks.

Mobile Support Systems (MSSs) assist maintenance workers on site in remote locations by providing, for example, billing data or manufacturer documents to a mobile device. MSSs are mainly used as data aggregators or presentation devices and for dispatching tasks to maintenance workers.

Condition Monitoring Systems (CMSs) have the task of continuously monitoring individual machines or complete systems. If the measured state has a large deviation from the theoretical state, the CMS will generate an appropriate message to inform (for example) the operator.

E-Maintenance (E-MS) is a term that emerged in the early 2000s (Iung et al., 2009), linked to the increasing use of ICT in general and by the Internet in particular (Li et al., 2005). The term "E-MS systems" is used to describe a variety of diverse systems with modern technologies, ranging from remote maintenance systems (Iung, 2003) to CMMS with enhanced web technology (Hausladen and Bechheim, 2004).

Intelligent Maintenance Systems (IMSs) were developed by (Lee et al., 2006) at the same time as E-MS. (Ling Wang et al., 2006) defines the IMS core paradigm of allowing error prediction by means of sensor analysis and prediction of performance degradation of a component. With this definition, the IMS concept is strongly linked to predictive maintenance and CMS.

The focus of Predictive Maintenance Systems (PMSs) is similar to that of IMSs but with more emphasis on error prediction and avoidance, based on algorithms and data mining techniques. The term and linked technology are somehow the trending topics for maintenance IS due to the rise of data mining and artificial intelligence. Another reason for this popularity is the increase in big cloud providers who offer services especially for predictive maintenance.

Decision Support Systems (DSSs) emphasize the aspect of data analysis and presentation in order to facilitate the analysis of the current situation by means of modern algorithms, allowing decision makers to make informed decisions.

2.4 Architectural Considerations when Implementing New Maintenance Systems

The systems presented here outline the challenges that arise in the development of holistic ISs to support maintenance. Information from a large number of systems is required, which is why the architecture of an IS has to deal primarily with data integration and interfaces. Furthermore, the number of support systems shows the many different facets in which maintenance can be supported. However, the distinction and inclusion of the relevant requirements, which lead to the respective systems, is often very difficult. The development of sustainable architectures also requires knowledge of the properties and requirements of the systems and thus of the overlapping core.

So far, however, no papers are known to us that relate these systems to one another and compare their characteristics and requirements. Only overviews of the requirements for MSSs can be found by (Matijacic et al., 2013). For this reason, relevant requirements are subsequently derived, based on these systems.

3 GATHERING REQUIREMENTS FOR MAINTENANCE INFORMATION SYSTEMS

A comprehensive perspective on maintenance ISs is needed to evaluate whether a requirement can be considered holistic. This holistic view has to aggregate all the aforementioned systems to distinguish special and common requirements and it needs to identify the most important ones for future maintenance ISs.

To establish this holistic view, requirements for individual ISs are gathered in this paper via a comprehensive literature review that will establish a holistic and interdisciplinary view of maintenance ISs.

3.1 Literature Review Approach

The literature review was conducted in 2017 via a comprehensive database search. The aim of the literature review was not to show that the literature search found every relevant article. Instead, the articles found needed to demonstrate a broad basis of the diverse systems as viewed from a variety of research directions, in order to achieve an interdisciplinary view on requirements. For this reason, Google Scholar was used as a search engine/database. Thus, not only could very special and exact search terms be used, but also very far-reaching ones.

Keywords were extracted by the above systems, maintenance concepts, strategies, methods, and technologies used. These keywords were combined with the terms 'system', 'requirement' and/or 'maintenance' to form a search string that certainly had a relation with these terms. If the system names varied between German and English, additional German search terms were employed. A combined total of 43 search terms were used. Only articles from 2005 to the present were examined.

All the articles resulting for each search term were investigated unless there were more than 80 results per search term. In these cases, only the top 80 were investigated because the relation to the search term and the relevance decreased with each result.

The results were examined to determine whether they contained requirements for ISs for maintenance in general or for a specific IS. These requirements can be explicit or implicit. In the case of explicit requirements, these are named exactly. For example, either by presenting requirements for a system or by a literature overview of requirements for a system or framework. Implicit requirements, on the other hand, can be reliably derived from descriptions of systems or frameworks. They are not mentioned directly, but they can certainly be deduced from the functions or descriptions in the articles.

The results of the respective search terms were first classified according to the title, keywords, and abstract only if they were considered relevant. During this process, 405 relevant papers were identified. The papers were then further examined and the entire contents of the paper were analysed. In this step, the requirements were also extracted. In total, 61 relevant papers were investigated that dealt with requirements for maintenance ISs or requirements could be derived.

In order to avoid a situation where requirements for a particular prototype, which was treated in several of the papers found, were included multiple times in the analysis, these requirements were normalized. Papers dealing with the same specific prototype therefore count as one publication and all the extracted requirements from the individual publications were summarized in this publication. However, they only count once.

After removing these papers, a total of 56 articles remained for inclusion in the requirements analysis for a holistic maintenance IS. The results are summarized in Table 1.

Table 1: Summarized results of literature search.

Search strings	43
Overall results	3115
Relevant results	405
Papers used	61
Papers used without duplicates	56

3.2 Resulting Requirements

Several steps were taken to gather the requirements from the papers:

- Extracting the explicit and or implicit requirements in original form
- In the next step, not mentioned requirements that are prerequisites by already extracted requirements were added as if they belonged to the article
- Similar requirements were unified and standardized. Afterwards, the requirements were clustered into topics

In total, 135 different requirements were identified in all the articles. In summary, the 135 requirements were identified 751 times in all articles.

These numbers show that requirements occur multiple times across different publications in relation to different systems and domains.

Table 2: Summarized results of literature search.

Condition Monitoring	31
Order Management	27
Error/Failure History	27
Overview of plants including specific plant related information	24
Remote maintenance with a focus on remote monitoring	22
Information on measures and tooling history of plants	22
Knowledge management	21
Condition history of parts/plants	19
Spare parts management (storage location, availability, costs)	18
Predictive maintenance	18
Provide maintenance plans/schedules for plants	16
Performance assessment and verification of the plants	15
Document management (storage, provision, sharing of documents)	15
Communication and contact with other persons (e-mail, messages, telephone)	14
Optimization of maintenance with respect to orders, inspections etc.	13
Component overview of plants	13
Presentation of the state of the plant on dashboards	13
Remote access (changing settings, controlling components)	12
Intelligent planning and scheduling of employees	12
Spare parts, material and possible tool lists per order	12
Display of an overview of internal and external experts for maintenance	12
Error message with detailed description	12

Table 2 summarizes all requirements found in the literature that occur at least 12 times. As a result, the requirements are seen in this article as top requirements. The names of the requirements have been partially truncated or aggregated.

We can see that the “Condition Monitoring” requirement or the requirement block is stated in more than half of all publications. Despite the fact that only 13 publications dealt with condition monitoring in detail, it can be said that condition monitoring is important for a broad range of maintenance ISs.

Order management and failure history are two requirements that are also broadly represented in the publications. An order management system, which manages incoming orders and tasks while monitoring ongoing ones, is essential for most ISs for maintenance if they want to be productive. In many cases, order management was performed by external systems that were not specially stated.

Supervision and monitoring were other important requirements. An overview of plants with information on spare parts, functionality and location was a top requirement. Linked to this, the ability to monitor the plant via remote maintenance is an essential requirement for many publications. Yet there is a difference between remote maintenance with a focus on monitoring and remote maintenance enabling direct access to the plant. This requirement was also a top requirement, but had only a value of 12.

Other important requirements with more than 17 occurrences were the provision of information on measures, tools and the history in general of a plant, the requirement for knowledge management (especially for knowledge of how to repair certain plants) and general knowledge for maintenance personnel. Another important requirement was the need to save and maintain access to the condition history of the plant and machinery. These are especially important for analysis and failure analysis. Connected with this requirement is the requirement for predictive maintenance, counted 18 times, which in fact was in most cases separated from condition monitoring as predictive maintenance is a forecast and data mining techniques are used sometimes.

Spare part management was also a very important issue, which should be handled via IS. This requirement includes the integration of spare part ordering and its connection to failures or orders, so that maintenance personnel knows beforehand which spare parts are needed for a job. Additionally, the need to automatically mark used spare parts was mentioned in this requirement.

These requirements, only 22 in all, have a total count of 388 of 751 of all requirements and cover almost ~52% of all mentions. Thus, one can say that some of these requirements or parts of them are the basis of nearly all the systems investigated.

Considering the impact these requirements can have on the architectural consideration of a holistic maintenance information system, the need arise to integrate them into planning as early as possible. A framework will be presented in the next section to do this and to integrate the requirements not explicitly mentioned.

4 FRAMEWOK FOR DEDUCING THE ARCHITECTURAL REQUIREMENTS

The top requirements, like the rest of the 135 requirements, can be classified into specific categories.

These categories, in addition to the top requirements, are designed to facilitate architectural decisions on new ISs for maintenance. The relevant requirements are known and can be classified more easily through the categories and the top requirements. Furthermore, software architectures and experts can compare their own requirements with those in the framework, identify their own and recognize interactions. Besides this, the architecture and the development of the categories can assume an early form of modularization. Interactions on a higher level can also be investigated.

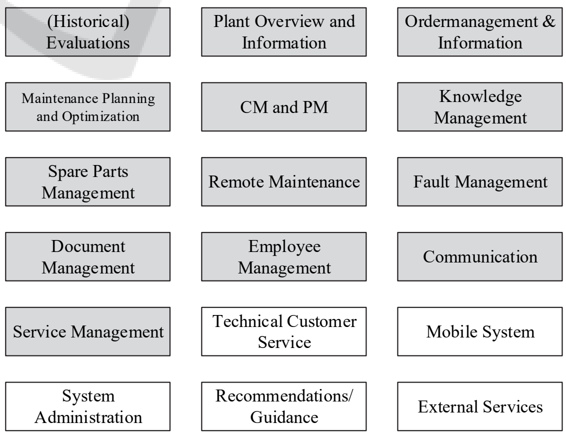

Figure 3: Clustered categories for requirements.

All the requirements were initially grouped into diverse categories. This classification was refined systematically through an iterative process. Finally, the following categories were identified in which the requirements for a maintenance IS can be assigned. The categories are shown in Figure 3. They are displayed, from the top left to the bottom right, according to the sum of the mentions of the individual requirements and the number of top requirements. Grey blocks contain top requests, while white blocks do not.

The individual categories are presented below with reference to exemplary requirements:

- (Historical) Evaluations: The category with the highest number of mentions of requirements is the (historical) evaluation. Four of the top requirements are in this block that deals with failure, order and condition histories, as well as with the evaluation of performance connected with these aspects.
- Plant Overview and Information: This category contains all requirements that provide information about plants. This includes requirements such as an overview of all plants and their properties, as well as a component overview for every plant. In addition, technical documents, such as manuals, for example, should be directly accessible.
- Order Management & Information: Order management for incoming orders and the management of tasks is necessary in a broad variety of systems. In this category, requirements for order management and the connected information about the order can be found. Furthermore, the section includes employee-oriented features, such as an individual overview of own tasks and the possibility to accept and reject tasks. It also includes aspects such as connecting an order with the required skills, and the ability to prioritize orders. Considering architectural implications, this category comprises a managing core for most maintainer-oriented systems because most information from other categories have to be connected with the corresponding order.
- Maintenance Planning and Optimization: In this category, features for optimization can mostly be found. The optimization of the order management or an intelligent disposition of the workforce considering their locations, skills and failure priorities are examples. In addition, requirements for a risk classification or integrated cost management are also assigned to this category.
- CM and PM: In this category, requirements that deal with condition monitoring and predictive maintenance can be found. On the one hand, the most frequently mentioned requirement, namely to determine the condition of a machine, is present in this category, together with further requirements for the visualization of this state. On the other hand, there are requirements in this category that are related to the prediction of errors and the use of data-mining techniques.
- Knowledge Management: Requirements for knowledge management can be found in this category. The most frequently cited requirement in this category is the knowledge management as an aggregation. This requirement is specialized in other requirements, which mainly deal with the storage, restoration and linking of knowledge with the concrete task.
- Spare parts management: This category of requirements is all about the management of spare parts. This includes the display of required spare parts, their availability, costs and storage location. Further requirements for the (automatic) ordering, forecasting and links to current orders are among other things grouped in this category.
- Remote Maintenance: The category of remote maintenance covers primarily the read access and thus contains remote maintenance as a top requirement. In addition, the requirements dealing with writing access and remote access and control for plants are illustrated here. There are also special requirements for the audio and video transmission of the machine data.
- Document management: The document management category includes requirements for managing documents, for the partially automated documentation of completed orders, and for fill-in assistants for specific forms and reports.
- Fault management: Failure management includes requirements for the fault messages of the systems and the system. Above all, a detailed error message is required. Moreover, a fault report directly sent to the device used by the responsible person or error messages with cause-effect relationships and the possibility to prioritize errors and report them manually are requirements in this category.
- Employee Management: Requirements in this category are used to manage and overview employees in maintenance. This includes the provision of an overview of the internal and external competency providers with an

availability schedule, a potential system for measuring working time, provision of skill profiles or semi-automatic travel cost recording.

- Communication: Communication requirements include the ability to communicate with other employees and competencies for example via e-mail, SMS, or telephone. Additionally, message functionality, Web 2.0 capabilities for commenting solutions and feedback functions are generally mentioned as requirements in this category.
- Service Management: Maintenance management includes only three requirements. In particular, the provision of maintenance plans for the systems and their components, the possibility to manually define maintenance limits and to compile maintenance documentation.

The next two categories were unique to some special kind of systems and have no top requirement:

- Technical Customer Service: In this section the only requirement that is necessary for IS which is used to manage a technical customer service and the interaction with external customers. It contains the customer management, connections with a CRM, the display of customer information for the maintenance personnel on site and several interfaces for reporting faults.
- Mobile System: This category contains requirements for MSS or IS that support mobile devices. It is an optional block of requirements that only contains specific mobile features such as barcode scanning, offline mode, photo features or a wireless diagnosis with a mobile device.
- Recommendations/Guidance: The recommendations/guidance block mainly includes the feature to provide recommendations for specific errors, maintenance, or error diagnoses, and they are automatically attached to the job/order.

The last two blocks consist of a few requirements that deal with specific system administration requirements and specific integrations of external services. All of the requirements have a low value and seem not very important for most authors. Yet the functions seem to be necessary for the most productive systems.

5 CONCLUSION

Contrary to the assumption that the many existing systems for maintenance are very different, the result of this article shows that maintenance systems have a generic core. This should be considered in future developments and the framework presented can support this.

The framework consists of 18 categories, which together contain 135 requirements. Of these 135 requirements, 22 requirements are defined as top requirements covering 52% of all claims of requirements. In addition to the requirements in the framework, the most important potentially existing systems for the maintenance activity were presented in this article. A distinction was made between systems from which data is primarily extracted and systems that directly support maintenance.

By providing this information, the framework helps to simplify the development and the selection of maintenance ISs of various types.

Through the structured overview of a holistic view on requirements for a maintenance IS impacts and future developments can be better assessed. Further, architecture requirements can be compared and derived. Building on this knowledge of existing ISs combined with the overview of requirements, the selection and development of ISs for maintenance can be facilitated by early interface considerations.

The framework offers an abstract basis for designing the architecture and deriving architectural components from the categories and examining existing architectures for the extension with regard to different requirements.

The various requirements and their categorizations also reveal the problem of the fragmentation of the individual services for maintenance, since data must be obtained from a variety of individual systems and services to form a holistic entity.

In the future, a reference architecture for holistic maintenance systems needs to be developed based on these findings, which will not only enable the core of a maintenance system to be displayed technically. It should also enable various existing services and systems to be combined in such a way that synergies are created.

ACKNOWLEDGEMENTS

Thanks are due to the Bundesministerium für Bildung und Forschung (BMBF) for financial support of this work within the project PRODISYS (FKZ 02K16C050).

REFERENCES

Bauernhansl, T. (2014) Die Vierte Industrielle Revolution – Der Weg in ein wertschaffendes Produktionsparadigma, in Bauernhansl, T., ten Hompel, M., and Vogel-Heuser, B. (eds) *Industrie 4.0 in Produktion, Automatisierung und Logistik*. Wiesbaden: Springer Vieweg, pp. 5–36.

Daeuble, G. et al. (2015) Information Needs of the Mobile Technical Customer Service -- A Case Study in the Field of Machinery and Plant Engineering, in *2015 48th Hawaii International Conference on System Sciences*. Kauai, HI, USA: IEEE, pp. 1018–1027.

DIN 13306:2015-09 (2015) *Instandhaltung - Begriffe der Instandhaltung; Deutsche und Englische Fassung prEN 13306:2015 (Entwurf)*. Edited by DIN Deutsches Institut für Normung e.V. Berlin: Beuth Verlag.

Fellmann, M. et al. (2013) Towards a Mobile Technical Customer Service Support Platform, in Daniel, F., Papadopoulos, G. A., and Thiran, P. (eds) *Mobile Web Information Systems*. Berlin Heidelberg: Springer, pp. 296–299.

Gabbar, H. a. et al. (2003) Computer-aided RCM-based plant maintenance management system, *Robotics and Computer-Integrated Manufacturing*, 19(5), pp. 449–458.

Galar, D. (2014) CONTEXT DRIVEN MAINTENANCE: An eMAINTENANCE APPROACH, *Management Systems in Production Engineering*, 3(15), pp. 112–120.

Gubbi, J. et al. (2013) Internet of Things (IoT): A vision, architectural elements, and future directions, *Future Generation Computer Systems*, 29(7), pp. 1645–1660.

Hausladen, I. and Bechheim, C. (2004) E-maintenance platform as a basis for business process integration, in *2nd IEEE International Conference on Industrial Informatics, 2004. INDIN '04.* Berlin, Germany: IEEE, pp. 46–51.

Horváth, P. (2017) Geschäftsmodellinnovationen durch Digitalisierung – Neue Herausforderungen an den Controller, in *Technologie, Strategie und Organisation*. Wiesbaden: Springer Fachmedien Wiesbaden, pp. 113–125.

Iung, B. (2003) From remote maintenance to MAS-based e-maintenance of an industrial process, *Journal of Intelligent Manufacturing*, 14(1), pp. 59–82.

Iung, B. et al. (2009) Conceptual framework for e-Maintenance: Illustration by e-Maintenance technologies and platforms, *Annual Reviews in Control*, 33(2), pp. 220–229.

Lasi, H. et al. (2014) Industry 4.0, *Business & Information Systems Engineering*, 6(4), pp. 239–242.

Lee, J. et al. (2006) Intelligent prognostics tools and e-maintenance, *Computers in Industry*, 57(6), pp. 476–489.

Lee, J., Bagheri, B. and Kao, H.-A. (2015) A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems, *Manufacturing Letters*. Society of Manufacturing Engineers (SME), 3(January), pp. 18–23.

Li, Y. et al. (2005) An Agent-based Platform for Web-enabled Equipment Predictive Maintenance, in *Proceedings of the 2005 IEEE/WIC/ACM International Conference on Intelligent Agent Technology (IAT'05)*. Compiègne, France: IEEE, pp. 132–135.

Lin, S.-W. et al. (2015) *Industrial Internet Reference Architecture*, *Technical Report*. tr. 001. Industrial Internet Consortium. Available at: http://www.iiconsortium.org/IIRA.htm (Accessed: 3 September 2015).

Ling Wang et al. (2006) Advanced Maintenance Strategy for Power Plants - Introducing Intelligent Maintenance System, in *Proceedings of the 6th World Congress on Intelligent Control and Automation*. Dalian, China: IEEE, pp. 7444–7448.

Maier, R. (2007) *Knowledge Management Systems*. 3. Berlin, Heidelberg: Springer.

Matijacic, M. et al. (2013) Elicitation and Consolidation of Requirements for Mobile Technical Customer Services Support Systems, in *Proceedings of the 34th International Conference on Information Systems (ICIS), Milan (Italy), December 15-18, 2013*. Milan, Italy, pp. 1–16.

Niu, G., Yang, B. S. and Pecht, M. (2010) Development of an optimized condition-based maintenance system by data fusion and reliability-centered maintenance, *Reliability Engineering and System Safety*. Elsevier, 95(7), pp. 786–796.

Reidt, A., Duchon, M. and Krcmar, H. (2017) Erstellung einer Referenzarchitektur anhand von individuellen Unternehmensanforderungen, in Bullinger-Hoffman, A. C. (ed.) *Abschlussveröffentlichung S-CPS: Ressourcen-Cockpit für Sozio-Cyber-Physische Systeme*. Chemnitz: Verlag aw&I - Wissenschaft und Praxis, pp. 23–42.

Zhu, J., Ong, S. K. and Nee, A. Y. C. (2014) A context-aware augmented reality system to assist the maintenance operators, *International Journal on Interactive Design and Manufacturing*, 8(4), pp. 293–304.