# Advantages and Potential Challenges of Data management in E-Maintenance

## Purpose

The purpose of this research paper is firstly to understand data management challenges in E-Maintenance systems from a holistically viewpoint through summarizing the earlier scattered research in the field, and secondly to present a conceptual approach for addressing these challenges in practice.

## Design/Methodology/Approach

The study is realized as a combination of a literature review and by the means of analyzing the practices on an industry leader in manufacturing and maintenance services.

## Findings

This Research provides a general understanding over data management challenges in E-Maintenance and summarizes their associated proposed solutions. In addition, this paper lists and exemplifies different types and sources of data which can be collected in E-Maintenance, across different organizational levels. Analyzing the data management practices of an E-Maintenance industry-leader provides a conceptual approach to address identified challenges in practice

## Research limitations/implications (if applicable)

Since this paper is based on studying the practices of a single company, it might be limited to generalize the results. Future research topics can focus on each of mentioned data management challenges and also validate the applicability of presented model in other companies and industries.

## Practical Implications (if applicable)

Understanding the E-Maintenance related challenges helps maintenance managers and other involved stakeholders in E-Maintenance systems to better solve the challenges.

## Originality/Value

The so-far literature on E-Maintenance has been studied with narrow focus to data and data management in E-Maintenance appears as one of the less-studied topics in the literature. This research paper contributes to E-Maintenance by highlighting the deficiencies of the discussion surrounding the perspectives of data management in E-Maintenance by studying all common data management challenges and listing different types of data which need to be acquired in E-Maintenance systems.

## Keywords

E-Maintenance, Maintenance Data, Data Management, Data Quality, Data Acquisition

## 1. Introduction

E-Maintenance is an interdisciplinary approach to asset management, which thanks to Information and Communication Technologies (ICTs), integrates and synchronizes various maintenance and reliability functions, such as monitoring, diagnosis, prognosis and decision processes, and delivers asset information where and when needed (Muller *et al.,* 2008, Holmberg *et al.* 2010). Gathering all maintenance strategies in one place, E-Maintenance incorporates maintenance with manufacturing and overall business operations by establishing an overlaying function over different organizational structures and links isolated processes into one transparent, integrated, and value-adding system (Hausladen and Bechheim, 2004, Holmberg *et al.* 2010).

E-Maintenance creates a platform for sharing data all over the enterprise, increases the process efficiency and results in more cost-effective decisions (Jordan and Ellen, 2009). In E-Maintenance systems, it is easier to acquire data from different sources, process larger data sizes and increase data usability to assure information quality for a more productive maintenance system (Candell *et al.,* 2009; Muller *et al.,* 2008). E-Maintenance especially plays a key role in those cases where delivering different information to various stakeholders is essential (Kour *et al.,* 2014).

Integration of different systems, however, makes E-Maintenance more complicated and higher volumes of data must be generated to assure availability of overall system (Karim *et al.,* 2009). An E-Maintenance system involves a wide variety of data including maintenance data, product data and operational data that all are gathered from heterogeneous sources, requiring to be processed and merged, in order to optimize maintenance decisions (Aljumaili *et al.,* 2015, Kobbacy *et al.* 2008). Moreover, in E-Maintenance, data is gathered for versatile purposes such as planning, observing and assessing equipment's condition and to support different maintenance processes (Murthy *et al.,* 2015). Collecting a wide variety of data for the purpose of E-Maintenance involves data management challenges, which have not been studied adequately in academia before.

According to Aboelmaged (2015), E-Maintenance research has flourished between 2010 and 2012. The so-far published articles on E-Maintenance can be categorized in three main classes: 1) Articles which research E-Maintenance concept from different perspectives (e.g. Aboelmaged (2015), Jantunen *et al.,* (2010), Muller *et al.,* (2008), Levrat *et al.* (2008)). 2) Articles which propose platforms for implementing E-Maintenance (e.g. Verma *et al.,* (2010), Bangemann *et al.,* (2006), Han and Yang (2006), Hausladen and Bechheim (2004)). 3) Articles which study E-Maintenance from data and information management perspective (e.g. Aljumaili *et al.,* (2015), Kour *et al.,* (2014), Campos (2014), Tretten and Karim (2014), Karim *et. al.,* (2009)). Regardless of the variety of previous discussion, particularly the discussion on data and information management in the E-Maintenance context has been lacking.

The aim of this research is two-fold: to understand data management challenges in E-Maintenance systems from a holistically viewpoint through summarizing the earlier scattered research in the field, and to present a conceptual approach for addressing these challenges in practice. The study is based on a literature review and analyzing the practices of an E-Maintenance organization that is a global market-leader, in manufacturing and maintenance services.

The remainder of this paper is organized as follows: Section 2 discusses the research methodology. Section 3 contains literature review in the context of data management challenges in E-Maintenance. Section 4 presents the analysis of the selected company in order to validate the findings from literature and map the current system. Section 5 discusses the results and proposes an improved future-state, followed by scientific and managerial implications. Finally section 7 concludes the paper.

## 2. Research Method

The ultimate objective of this research is to discover data management challenges in E-Maintenance systems. To achieve this goal, A literature review was performed to summarize earlier diverse research in E-Maintenance field in context of data management. Literature review consists of an extensive review of peer-reviewed journal, scientific conference papers as well as textbooks, dealing with Maintenance and E-Maintenance in general and data management in particular.

Studied papers were selected through an electronic search in accredited databases, such as *ScienceDirect*, *Emeralds* and *SpringerLink*. Keywords used for electronic search include "E-Maintenace data", "maintenance data", "condition monitoring data", "data management in E-maintenance", "ICT technologies in maintenance". In addition to peer-reviewed journal and scientific conference papers, a number of maintenance and E-Maintenance- related textbooks were also studied.

In addition to reviewing and summarizing E-Maintenance literature, the data management practices of a global E-Maintenance organization were studied in order to present a conceptual framework for addressing data management challenges in industrial context. Figure 1 shows the initial understanding of the research process.
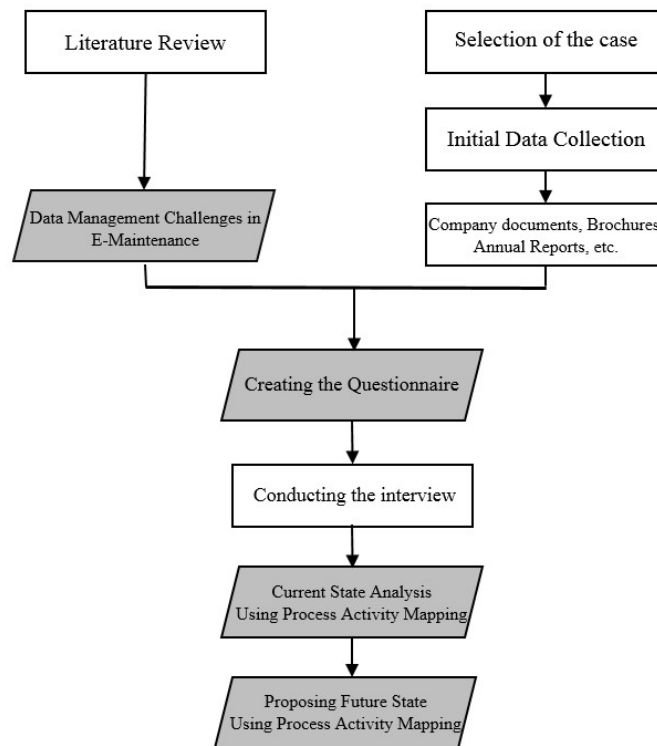


**Figure 1.** Initial Understanding of the Research Process.

### 2.1. Selection of an E-Maintenance Organization to study

In order to select the right industrial organization to analyze data management in E-Maintenance , two major factors were considered: 1) the size of the organization and 2) the criticality of E-Maintenance for the company. According to these criteria, an industry-leading company which manufactures industrial machines and offers maintenance services to a large group of customers from various industries such as manufacturing, process and harbors was selected.

The selected company manufactures industrial equipment through a set of internationally-known brands. In addition, the company has about 600 different service locations in 50 countries world-wide and offers a variety of maintenance and modernization services. It owns the most extensive service network in its industry, covering 450,000 units, where most of them have not been manufactured by the company itself. Industrial internet is one of the main building blocks, on which the company has been founded. The novel E-Maintenance services, offered by the company constitutes 55% of its personnel and 44% of its annual turnover.

## 2.2. Data Collection

Data triangulation increases the validity of the findings and helps researcher to better perceive the complex systems. Therefore, in order to cross-verify and validate the collected data, Data Source Triangulation and Methodology Triangulation have been utilized. In order to gain an inclusive and deep insight on data management in E-Maintenance systems, data about the E-Maintenance system of the studied company, has been collected in different forms, including product brochures, service catalogues, annual reports and company's confidential materials, Along with analyzing the content of acquired data, an extensive qualitative research was conducted, aiming to understand the common data management challenges in E-Maintenance. In Methodology Triangulation, multiple methods have been implemented to collect data, such as reading documents, field observations, creating questionnaires and conducting interviews.

Identifying data management challenges via literature review and acquiring versatile data through different data collection methods, provide a good basis for the interview part.Head of Product Lifecycle Management (PLM) in a leading E-Maintenance organization was interviewed in person and afterwards an electronic questionnaire was distributed in PLM department consisting 50 people. Questionnaire contained open questions, whereas the interviewees were free to share their knowledge and experience anonymously about the company's E-Maintenance system or even provide complementary information, in case not covered by the questionnaire."

Based on data collection and interview, current E-Maintenance platform of studied company is visualized by using *Process Activity Mapping* tool. The data management challenges and improvement needs have been argued in discussion part and finally the future-state is proposed accordingly.

## 3. Literature Review

Embracing different processes within and outside of an organization, high volumes of data need to be collected, stored, processed and shared in E-Maintenance systems. Different data management challenges are, however, present which need to be overcome in order to make timely and appropriate maintenance-related decisions. Table 1. Summarizes the most common data management challenges along with E-Maintenance implementation.

**Table 1.** Common Data Management Challenges in E-Maintenance

| Challenges | Description | Contributors |
|---|---|---|

| | | |
|---|---|---|
| Data Acquisition | Process of collecting various types of E-Maintenance data from objective and subjective sources | Wandt *et al.,* (2012), Murthy *et al.,* (2015), Jardine *et al.,* (2006), Aljumaili *et al.,* (2015), Tretten *et al.,* (2014), Campos, (2009), Karim *et al.,* (2016), March and Scudder, (2017) |
| Rapid Information Flow | Bi-directional and seamless flow of information among all stakeholders involved in different processes | Iung (2003), Arnaiz *et al.,* (2009), Lee, (2003), Candell *et al.,* (2009). Campos, (2009), Hausladen and Bachheim, (2004), Lee *et al.,* (2006), Zhang *et al.,* (2003), Wan *et al.,* (2016), Bousdekis *et al.,* (2017) |
| Data Quality | Collecting relevant, fit-for-use data from all stakeholders in E-Maintenance system and cleaning data from errors | Aljumaili *et al.,* (2015), Jardine *et al.,* (2006), Tretten *et al.,* (2014), Jantunen *et al.,* (2010), Tsang *et al.,* (2006), Lin *et al.,* (2006), Bergquist and Söderholm (2014), Karim *et al.,* (2016), |
| Voluminous and Heterogeneous Data | Dealing with large volumes of E-Maintenance data from heterogeneous sources that are different by nature | Bergquist and Söderholm, (2014) Campos, 2009; Arnaiz *et al.,* (2009), Levrat *et al.,* (2008), Murthy *et al.,* (2015), Aboelmaged, (2015), Muller *et al.,* (2008), Kour *et al.,* (2014), Iung *et al.,* (2009), Aljumaili *et al.,* (2015) Wandt *et al.,* (2012), Arnaiz *et al.,* (2009), Labib (2004), Wan et. al., (2016), March and Scudder, (2017), Bousdekis et. al., (2017) |
| Data Exchange and Interoperability | Sharing data and interconnecting all involved systems in E-Maintenance | Karim *et al.,* (2009), Lim and Klobas, (2000), Aljumaili *et al.,* (2015), Arnaiz *et al.,* (2009), Campos (2014), Karim *et al.,* (2009), Campos (2014), Wang and Xu (2013), Siegel (1998) |
| Data Conversion | Standardizing and unifying the data formats which are being used and shared by all parties in an E-Maintenance system | (Tsang, 2002), Koç *et al.,* (2003), Bangemann *et al.,* (2003), Moor and Starr, (2006), Karim and Söderholm, (2009), Jordan and Ellen, (2009), Jantunen *et al.,* (2010), Han and Young, (2006), Koç *et al.,* (2003), Lee *et al.,* (2006). |

Each of these challenges are discussed further in the following sections.

### 3.1. Data Acquisition

Data Acquisition is the process of gathering relevant data and managing its content effectively (Wandt *et al.,* 2012), and also the first step in E-Maintenance data management. Choosing the most appropriate data collection methods plays a deciding role in E-Maintenance data management due to related costs (Murthy *et al.,* 2015), and due to risks of inadequate or wrong data failing the entire maintenance system (Jardine *et al.,* 2006). Table 2 shows various types of data which are collected in E-Maintenance.

As a consequence of the importance of data for E-maintenance, a systematic approach to data acquisition is necessary (Jardine *et al.,* 2006) to gather products' and assets' data in all lifecycle stages and to distribute data to stakeholders in order to enhance systems' effectiveness (Murthy *et al.,* 2015).

Furthermore, the collected data should be relevant and sufficient, to enable extracting desired information to support the decision making process (Aljumaili *et al.,* 2015; Tretten and Karim*,* 2014). Collecting small or limited samples of data leads to poor modeling of maintenance system and consequently making poor maintenance decisions (Kobbacy *et al. 2008*). Furthermore, scarcity of timely and fact-based maintenance data, representing effectiveness of procurement, engineering and manufacturing, negatively impacts management of plants (Mobley *et al. 2008*).

**Table 2.** Different types of data collected in E-Maintenance

| Data Type | Examples | Description | Contributors |
|---|---|---|---|
| Maintenance Event Data | Technical data | Electrical and mechanical data, manufacturer and equipment specification details, and the guarantee period which is necessary for external maintenance engineers and workers | Kelley (1997), Kelley (2006a), Kelley (2006b), Kelley (2006c), Tsang *et al.,* (2006), Muller *et al.,* (2008), Mobley *et al.* (2008) Tretten and Karim (2014), Wan *et al.,* (2016), Lee and Pan (2017), Bousdekis *et al.,* (2017) |
| | Technical Drawings | Includes both manufacturer and user drawings that are gathered by engineering department and necessary to be updated. | |
| | Maintenance Manual | Instructions on how to maintain the failed item, or equipment, which like technical drawings require updating. | |
| | Spares Part Lists | A list of all spare parts stored in warehouse for each unit, accompanied with manufacturers' Bill of Material (BOM), same or similar parts. | |
| | Equipment Life Plan | A calendar-like plan that shows the inspection intervals for PM | |
| | Maintenance Job Catalogues | Shows the work order, work request, actions which should be carried out in inspections and corrective maintenance actions, in case a degradation has been noticed and cost code for the action implemented | |
| | Maintenance Control Information | Contains information on maintenance costs, plant availability and reliability control, and includes plant history data such as failure's date, duration and cause as well as production or quality losses | |
| | Operation and Safety data | Uncertainties and risks related to nature of maintenance actions, conditions under which the maintenance action need to be done, sharing of safety rules | |
| Condition Monitoring Data | Value type | Condition monitoring data that are collected at a point of time and have single value | Jardine *et. al.* (2006), Tsang *et al.,* (2006), Mobley, *et al.* 2008, Hästbacka *et al.* (2016), Karim *et al.,* (2016), Lee and Pan (2017) |
| | Waveform type | Condition monitoring data, collected at a point of time, based on time-series and have a trend over time | |
| | Multi-dimensional | Condition monitoring data, collected at a point of time and are multidimensional | |
| Product Data | product structure (BOM) | product specifications, product faults and failure modes, etc. | Kelley (2006a), Kelley (2006b), Kelley (2006c), Murthy et al., (2015) Wan et al., (2016), Karim et al., (2016) |
| Business Data | e-Procurement data | Spare parts' electronic ordering, Spare parts' order status, Spare parts' shipment notice, on-line payment and invoicing | |
| | Customer Relationship Management (CRM) data | Maintenance support and after-sale services, maintenance service ticketing | |
| | Supplier Relationship Management (SRM) data | Sharing of maintenance data, joint training of maintenance personnel and mutual investment on maintenance technology acquisition | |
| | Human Resource Management data | Planning and assigning local and external maintenance personnel to tasks | |

E-Maintenance data can be collected from either subjective or objective sources (Aljumaili *et al.,* 2015). Subjective data deals with subjective judgement and assumptions made by human experts and decision makers while objective data is unbiased due to be free from human hypotheses and is created via computer models and sensors (Aljumaili *et al.,* 2015). Regardless of the source, data needs to be consistent, highlighted by E-Maintenance systems requiring large volumes of data form various sources that can be geographically dispersed (Campos, 2009; Murthy *et al.,* 2015).

### 3.2. Rapid Flow of Information

E-Maintenance is an intelligent and knowledge-based maintenance system that involves a rapid flow of information among diverse groups of actors who utilize the shared insights from remote monitoring of assets to decide about equipment's diagnosis, degradation and future Remaining Useful Life (RUL) in a collaborative fashion (Iung, 2003).

The integration of different business processes in E-Maintenance systems, removes isolated islands of information and creates a bi-directional flow of information and knowledge which improves the quality of decision making (Moore and Starr, 2006). Moreover, in contrast to conventional maintenance approaches where information flow is uncooperative, in E-Maintenance information exchange has approximated working relations (Candell *et al.,* 2009).

Although merging maintenance-related business processes supports better information flows at all levels (Campos, 2009; Hausladen and Bachheim, 2004) and results in lower system downtime (Lee *et al.,* 2006), it has also some negative sides. In some maintenance systems, lack of continuous and seamless flow of information hinders instant understanding and usefulness of collected data (Kobbacy *et al. 2008*). In more sophisticated systems, information flow is faster (Candell *et al.,* 2009), while in E-Maintenance each involved system should control information flow (Zhang *et al.,* 2003). Each actor involved in E-Maintenance must be able to follow the rapid information flow (Muller *et al.,* 2008), therefore, the overall information flow should be constructed systematically to allow identifying how the overall system functions (Lee, 2003).

### 3.3. Data Quality

Data quality has been defined in the following manner: "the level of quality of data represents the degree to which data meets the expectations of data consumers, based on their intended use of the data" (Sebastian-Coleman, 2012). Data quality is the process of assuring that data follows certain specifications and is fit for different organizational purposes (Jordan and Ellen, 2009). Data quality has different dimensions of data: accuracy, consistency, integrity and timeliness (Aljumaili *et al.,* 2015). Practically, data quality involves "cleaning" data from errors manually or by using computerized graphical tools to have high quality data from data collection to further data modeling, analysis, fusion and integration processes (Jardine *et al.,* 2006). Data cleaning is an ongoing process which should be carried out with limited manual and programming tasks, not only in data collection phase, but also as the data is being merged from various sources.

Collecting high-quality data significantly affects the success of an enterprise (Sebastian-Coleman, 2012). Without reliable data, maintenance organization cannot evaluate the advantages of its maintenance system (Mobley *et al.* 2008). Additionally, in E-Maintenance high quality data directly influence final decisions (Tretten and Karim, 2014), and regardless of how sophisticated the E-Maintenance technology is, collecting and feeding poor quality

data to the system results in low quality decisions, even referred to as "garbage in garbage out" (Jantunen *et al.,* 2010; Jardine *et al.,* 2006).

There are different reasons why data-quality problems occur in an E-Maintenance system. Maintenance event data which are collected manually from subjective sources contribute to 80 per cent of data-quality-related problems (Jardine *et al.,* 2006), On the other hand, in condition monitoring, poor quality data are caused by faulty sensors which may collect "noisy" data (Jardine *et al.,* 2006). Such data are filled with meaningless or truncated data that does not contain enough details (Lin *et al.,* 2006). This low quality data gathered in diagnosis stage, will be then used in modeling, resulting in adverse effect on prognosis stage (Bergquist and Söderholm 2014).

Assuring high-quality and promptness of data in E-Maintenance systems is highlighted due to versatile sources and sharing the data with different actors (Tsang *et al.* 2006). In fact, it can be better not to share any data if its quality is not controlled (Jordan and Ellen, 2009). In order to improve data quality, a clear and unified definition of data quality is necessary, including principles for developing processes of assuring data quality (Jordan and Ellen, 2009). It is essential that each organization involved in E-Maintenance can make enterprise-wide decisions for generating higher quality data (Sebastian-Coleman, 2012).

### 3.4. Voluminous and Heterogeneous Data

This challenge refers to large volumes of data that are generated, and acquired from heterogeneous sources. E-Maintenance data are collected from RFID tags, sensors, PDAs and maintenance operators in different stages of asset's lifecycle. Real-time data from heterogeneous environments, need to be aggregated to E-Maintenance information system (Aboelmaged, 2015; Muller *et al.,* 2008).

Although the advancements of ICTs have provided the foundation for collecting and processing massive data from diverse origins (Iung *et al.,* 2009), some challenges remain. Vast data from numerous sources, threatens the data quality and makes obtaining information and interoperability between systems problematic (Aljumaili *et al.,* 2015; Wandt *et al.,* 2012). Although merging information from multiple sources and collecting large volumes of data may support maintenance (Arnaiz *et al.,* 2009; Labib 2004), it impedes fault diagnosis and knowledge acquisition from uncleaned data (Kour *et al.,* 2014). In other words, acquiring large amount of data and consequently huge data analysis effort may outweigh the advantages of data collection (Mobley *et al.* 2008).

### 3.5. Data Exchange and Interoperability

Information should flow smoothly among all stakeholders, but collecting heterogeneous data impedes interconnectivity and integration (Karim *et al.,* 2009). Interoperability which is one of the most significant characteristics of an enterprise, is defined as the system's ability to share information or swap services between two or more systems and then co-operate based on the shared information or exchanged services.

Interoperability, considers data contexts within data systems and creates a common platform for data exchange (Aljumaili *et al.,* 2015), helps further different software systems to work together regardless of their location, operating system or programming language (Siegel, 1998). In order to assure interoperability, constituent systems should interpret data accurately and in a right context (Lim and Klobas, 2000). Standards, data exchange models and communication protocols further stabilize the data

delivery (Aljumaili *et al.,* 2015). They develop interoperability among multiple systems, including maintenance and manufacturing (Ray and Jones, 2006).

The tools that assure interoperability in E-Maintenance systems, include Web technologies (Arnaiz *et al.,* 2009; Campos, 2014; Karim *et al.,* 2009), Cloud Computing (Campos, 2014; Wang and Xu, 2013), and such. Web technologies provide a platform to share and reuse information among different applications and parties on the net via shared structures such as Semantic frameworks. Although, Semantic frameworks let involved actors manage data over the net (Campos 2014), one of the challenges in E-Maintenance is to fit the semantic framework for maintenance functions in a way that exchanged information over the internet can be defined for different E-Maintenance environments (Arnaiz *et al.* 2009). Cloud computing can also establish a basis for E-Maintenance actors to access, not only shared information, but also shared network, services and computing resources in real-time (Wang and Xu 2013).

### 3.5.1 Interoperability and Data Exchange Standards

Regardless of web-technologies and cloud-computing which are general solutions for data exchange, there are tools and standards created, for assuring interoperability in E-maintenance systems. International Organization for Standardization (ISO) has defined ISO 13374:2012 on Condition monitoring and diagnostics of machines - Data processing, communication and presentation. ISO-13374, defines six blocks of functionality in a condition monitoring system, as well as the general inputs and outputs of those six blocks. These six blocks include Advisory Generation, Prognostics Assessment, Health Assessment, State Detection, Data Manipulation and Data Acquisition (Prajapati *et al.* 2012). Table 3 lists some of condition monitoring standards, developed by ISO.

**Table 3.** Condition monitoring and diagnostics of machines - Data processing, communication and presentation standards, developed by ISO (ISO 2018)

| Standard | Subject | Scope |
|---|---|---|
| **ISO 13374**-1 | Condition monitoring and diagnostics of machines - Data processing, communication and presentation - Part 1: General guidelines | Provides general guidelines for software specifications related to data processing, communication, and presentation of machine condition monitoring and diagnostic information |
| **ISO 13374-2** | Condition monitoring and diagnostics of machines -- Data processing, communication and presentation - Part 2: Data processing | Explains reference information model and reference processing model, to which open condition monitoring and diagnostics (CM&D) architectures need to adapt |
| **ISO 13374-3** | Condition monitoring and diagnostics of machines -- Data processing, communication and presentation - Part 3: Communication | Details data communication requirements for an open condition monitoring and diagnostics (CM&D) reference information architecture and reference processing architecture |
| **ISO 13374-4** | Condition monitoring and diagnostics of machine systems -- Data processing, communication and presentation - Part 4: Presentation | Specifies the requirements, needed for presentation of information for technical analysis and decision support in condition monitoring and diagnostics open architecture. |

Another major contributor to maintenance data agreements is Machinery Information Management Open System Alliance (MIMOSA). MIMOSA is a non-profit industry association, dedicated to the development and adoption of open information standards for operations and maintenance applications in manufacturing, fleet, and facility environments (Campos, 2014). Table 4 shows the most common standards, developed by MIMOSA.

### 3.6. Data Conversion

One of the major threats in E-Maintenance data management, is information buried in E-Maintenance big data, originally generated through the system's lifecycle and ending up hidden in versatile places and formats (Tsang, 2002). This big raw data is usable only if it is converted into appropriate formats (Koç *et al.,* 2003). Linkage of different systems exacerbates the situation as involved actors need to share data in diverse locations, each using different data-formats and generating huge amounts of data (Bangemann *et al.,* 2003). This problem makes data incompatible and reduces the data quality, impeding the business processes (Bose 2006).

The solution to aforementioned problem, is standardizing the format in which data is archived, processed and then exchanged among distinctive systems (Karim and Söderholm, 2006). In fact, data should be delivered in an identical format to have a unified understanding of same data among different business systems (Jordan and Ellen, 2009).

Having identical data formats in maintenance, is needed in all stages of product lifecycle (Jantunen *et al.,* 2010). Therefore data conversion is a data pre-processing task and plays a vital role in optimizing maintenance systems (Kobbacy *et al.,* 1995). Hence, E-Maintenance system should have a scalable and reconfigurable platform, capable of converting data to information and information to knowledge, supporting harmonization with other processes (Han and Young, 2006; Koç *et al.,* 2003; Lee *et al.,* 2006).

### 4. Current State Analysis

E-maintenance data management process in the analyzed company has five different stages, namely: Data Collection, Data Transfer, Data Fusion, Data Analysis, Visualization or Information Sharing that are in line with the Aljumaili *et al.* (2015) and Jardine *et al.* (2006). Figure 2 shows this process. The process starts by acquiring versatile types of data from heterogeneous sources over different organizational levels. The purpose of data collection is defined collaboratively by customers and the studied company. This data collection also forms the basis for internal traceability of the products. An interviewee described the situation as: *"..., equipping assets and their components with e-technologies enables tracing products from top level of the asset (as a whole product), down to different levels of Bill of Material"*. Condition monitoring data are collected via sensors in real-time or entered manually through mobile devices such as smart phones or PC tablets by professional service technicians.

Although, the company has prepared standards for data collection based on different products, data collection can be affected also by customers' will and the industry they are active in. This was commented as: *"..., it could be also that there are other ways to reach safe service level with the customers like military and nuclear but in normal manufacturing type of approach customer does not have any problem with letting data go out of their premises."*

**Table 4**. Most common data exchange and interoperability standards, developed by MIMOSA

| Name of Standard | Scope | Advantages |
|---|---|---|
| Common Collaborative Object Model (**CCOM**) | An information model for the exchange of asset information and to facilitate standards-based interoperability between systems (MIMOSA 2018) | 1. Effectively representing data for the purpose of data exchange (MIMOSA 2018)<br>2. Providing a cleaner and more flexible model for Enterprise Application Integration (MIMOSA 2018) |
| Common Relational Information Schema (**CRIS**) | A relational database model for different data types which needed to be processed in condition-based maintenance (CBM) applications (Campos 2009) | 1. Enabling information and data exchange between plant and machinery maintenance information systems (Arnaiz et al. 2009)<br><br>2. Providing an open exchange standard in key asset management areas (Campos 2009) |
| Open System Architecture for Enterprise Application Integration (**OSA-EAI**) | A layered architecture to provide:<br><br>- An information exchange standard for asset registry, diagnostic and prognostic assessment, maintenance and reliability information between enterprise systems (Holmberg *et al..* 2010)<br>- Solves integration of different applications (Holmberg *et al..* 2010) | 1. Facilitating the integration of asset management information (MIMOSA 2018)<br><br>2. Provides flexibility with price of performance, in case all suppliers follow same standards (Holmberg *et al..* 2010) |
| Open System Architecture for Condition-Based Maintenance (**OSA-CBM**) | A standard architecture for information flow in CBM systems based on six blocks of functionality in condition monitoring systems (Prajapati *et al*. 2012), defined in ISO-13374 | 1. Enabling interoperability of CBM components (Holmberg *et al*. 2010)<br>2. Enabling software engineers to use a standard architecture for information flow in CBM systems (Holmberg *et al*. 2010)<br>3. Enabling all vendors to use same input and output interfaces (MIMOSA 2018)<br>4. Enabling Vendors to work on separate modules (MIMOSA 2018) |

The analyzed company acquires data both from subjective and objective sources: "*For the real-time (monitoring) it is all gathered by the sensors and then we go to more traditional type of maintenance, it is done mostly by human.*" The subjective and objective maintenance data are both treated as important and in some cases they complement each other. The use of humans was commented as:"*..., so it kind of means that we sometimes do not trust the data we gather from sensors and we send a technician. If sensors show that there was an overload or over-temperature, a technician will be sent to follow the case*".

In plant or organizational level, Manufacturing Data and Maintenance Service Data are collected from Production Planning System and maintenance event data, respectively. Comparing maintenance event data, such as maintenance logs and histories with real-time condition monitoring data results to estimation of Remaining Useful Life (RUL) of the asset. In Supply chain level, the latest data on spare parts inventory can be derived from Supplier Relationship Management System (SRM).

In Business level, there are three different types of data collected, namely Customer Data, Financial Data and Workforce Data. Customer Data are collected from CRM tool. An interviewee described the situation as: "*..., when an equipment's serial number is entered to the system, information such as customer's details, equipment's location, its usage and maintenance history, and its current condition can all be traced.* Financial Data such as maintenance cost controlling are acquired from Financial Data Management systems. Workforce Data which helps in planning and assigning maintenance engineers and technicians to maintenance actions are also captured from Human Resource Management System.

The collected data are then sent (Data Transfer) to a remote data warehouse, where they are centralized together (Data Fusion).
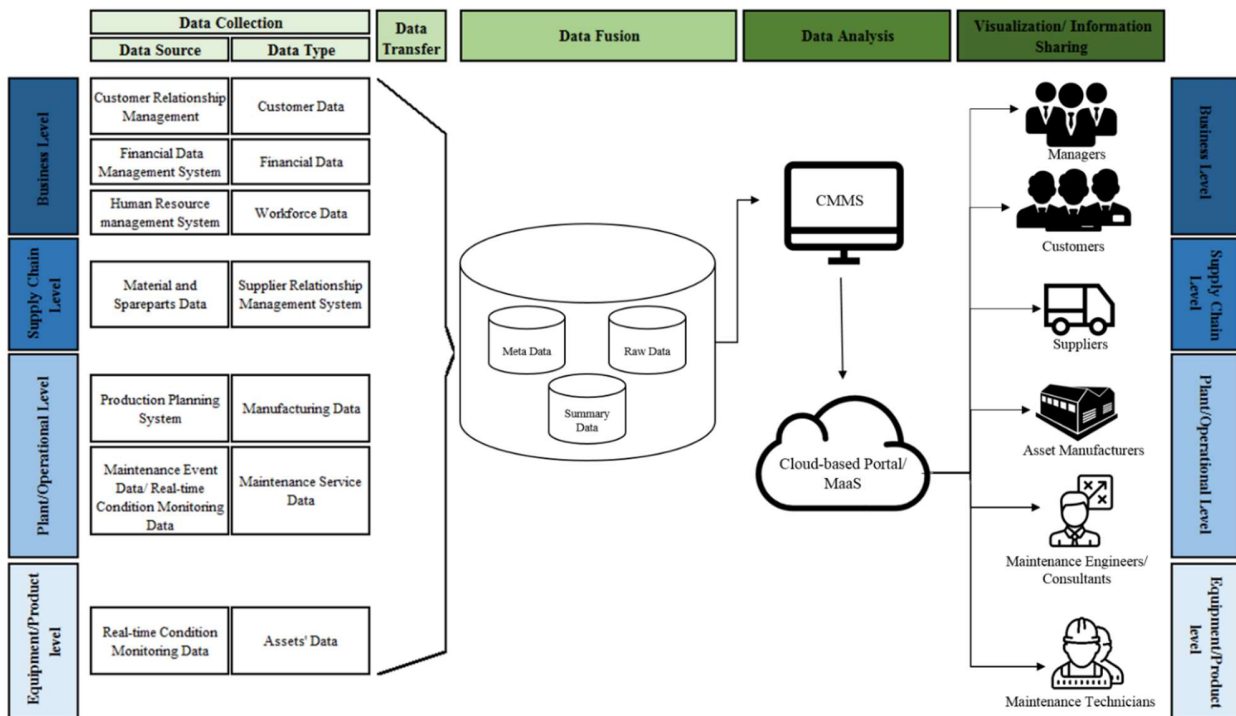


**Figure 2.** Data Management Process in E-Maintenance System of studied company

Aligned with Mobley *et al. (*2008), in Data Analysis stage, a Computerized Maintenance Management System (CMMS) parses the data. CMMS is a sophisticated standalone system within large maintenance organization or a fleet of assets which integrates maintenance-related data from various departments across the enterprise, aiming at enhancing maintenance plans. Analyzed data, including anomalies, trends, inter-related variables and patterns are then presented on a portal in a form of graphs, charts and tables for a single asset or whole fleet over any chosen time interval which provides the necessary data for scheduling both preventive and corrective maintenance tasks.

In Information sharing stage, the portal is a cloud-based platform which gives different stakeholders from different organizational levels a crystal clear overview of maintenance-related information. In Business Level, information can be shared with higher managers and customers (in case, the company is acting as a maintenance service provider). In Supply Chain level, information can be shared with spare parts and material suppliers to ensure Just-in-Time delivery of spare parts. As also stated by (Holmberg *et al.* 2010), this real-time information sharing thus establishes an open and virtual collaboration among different departments, facilitates decision making, and enhances the maintenance efficiency.

In Plant or Operational Level, The analyzed company, or the asset manufacturer can also use this data for Research and Development (R&D) and product development purposes. The use of the data was described by an interviewee as follows: "*R&D and product developments, so when we are having knowledge about our products that is one of the things and we always design products of high quality and safety, so these are also some of the things we are monitoring ourselves.*" Therefore, they can enhance products' quality and safety, and gain understanding whether the failed component has been produced in-house or supplied by a specific supplier. ".

After data has been shared with involved stakeholders, maintenance decisions are made. CMMS documents maintenance decisions and schedules maintenance actions. In Equipment or Product Level, maintenance technicians equipped with mobile devices can receive new maintenance schedules or maintenance manuals right on their mobile devices or Personal Digital Assistants (PDAs). After maintenance actions have been performed, technicians will update the maintenance history and document the maintenance action into the CMMS.

Figure 3 illustrates the analyzed E-Maintenance system, based on Process Activity Mapping. Process Activity Mapping is a preliminary tool related to lean methodology, practical for studying the process flow (Hines and Rich, 1997), supporting system engineers to understand the current processes, and to propose an improved future state
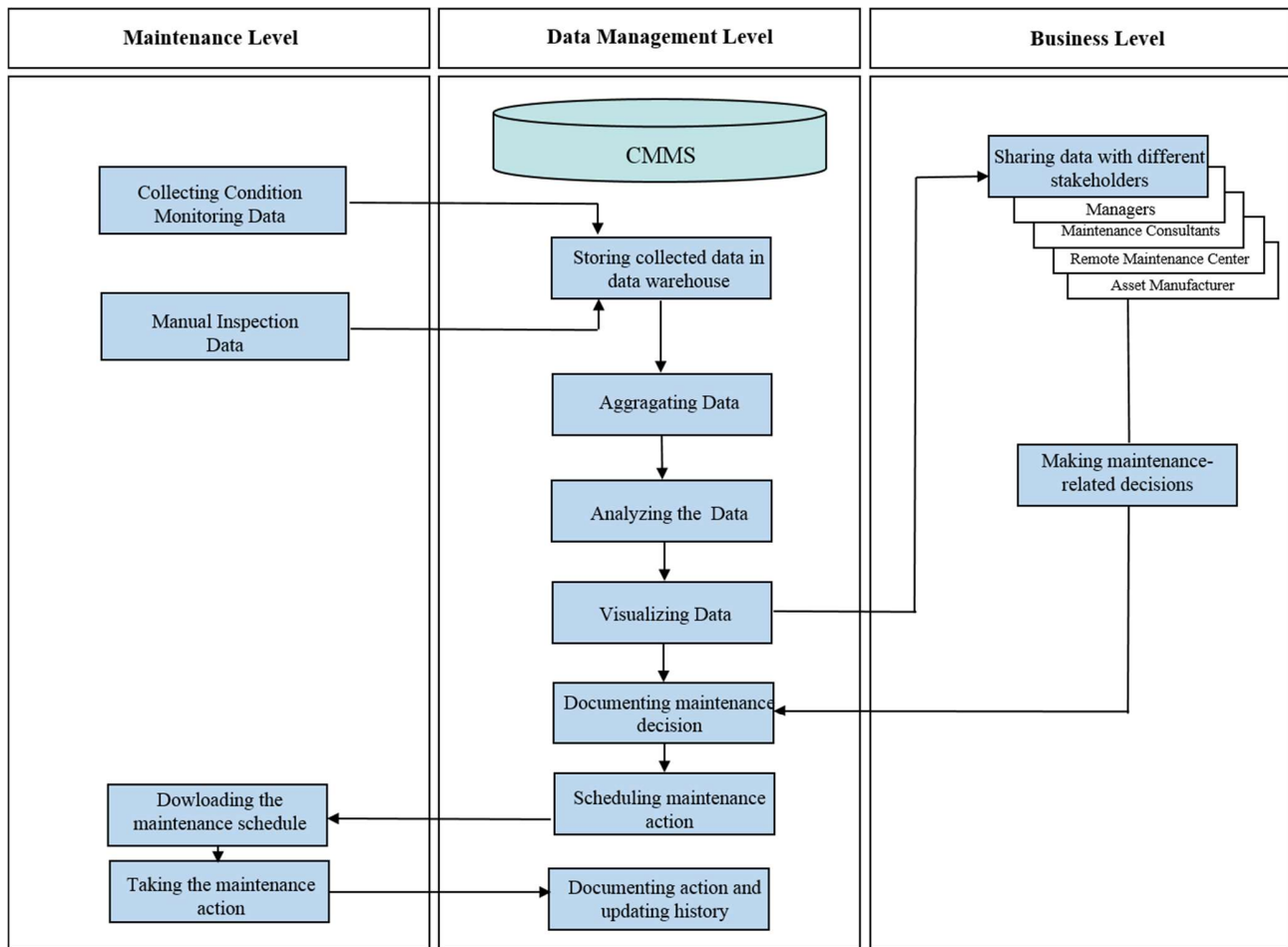
**Figure 3.** Analyzed E-Maintenance system

## 5. Discussion

Analyzing the current state of studied company's E-Maintenance validates the findings of literature review on data management challenges in E-Maintenance systems. The criticality of customers, number of stakeholders involved, type, size and complexity of services such as different geographical locations, are among the relevant challenges. Looking at the current state of E-Maintenance system, it has been observed that there are no actions on checking the collected data, whether or not it meets involved stakeholders' expectations. Therefore, in order to overcome data management challenges, following solutions are proposed (Table 5) and future state is distilled (Figure 4). This future state has been presented and discussed with studied company and feedback has been collected.

**Table 5.** Proposed solutions for overcoming data management challenges in E-Maintenance

| Challenges | Associated Problem | Proposed Solution |
|---|---|---|
| Data Acquisition | Collecting data from versatile resources that may be irrelevant and inadequate for maintenance decision making | Planning the data collection collaboratively with all involved stakeholders and defining the data collection KPIs |
| Voluminous and Heterogeneous Data/ Rapid Information Flow | Large volumes of data are generated, and acquired from heterogeneous sources | Acquiring the data according to defined data collection KPIs reduces the amount of collected data and as a result leads to a smooth information flow |
| | Lack of systematic information flow, causing fast flow of information in all directions among stakeholders | |
| Data Quality | Collecting noisy, truncated and meaningless data from objective and subjective sources | Automating the data collection through sensors, and prompt cleaning of data |
| Data Exchange and Interoperability | Lack of standards, data exchange models and communication protocols throughout the E-Maintenance system | Establishing compatible information systems inside and outside of stakeholders' organizations |
| Data Conversion | Converting raw E-Maintenance data into appropriate formats which can be utilized by all parties | Standardizing data formats within E-Maintenance system |
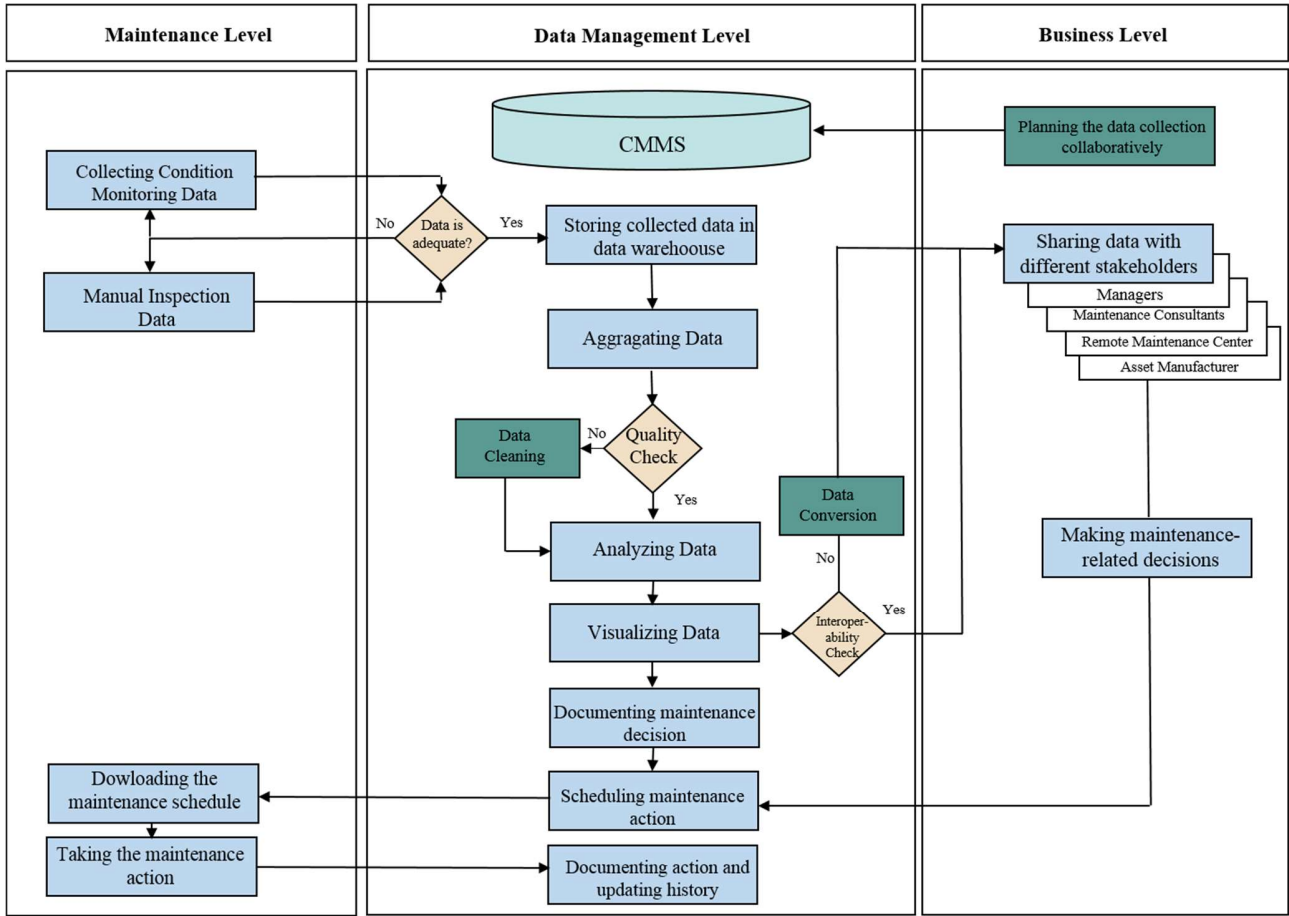
**Figure 4.** Proposed Process Activity Mapping for Future E-Maintenance system

Before data acquisition starts, the future E-maintenance requires that all involved stakeholders, managers, maintenance consultants and engineers, spare parts suppliers, assets manufacturer, and such, collaboratively define data acquisition standards and KPIs. Data acquisition is expensive. If there are no policies for collecting data or if there is no observance whether the collected data is relevant or sufficient for the aims of data collection, the quality of final decisions will be poor which lead to poor-quality actions. Therefore, In line with Mobley *et al.*(2008), it is of high importance that E-Maintenance system includes data collection and evaluation plans where all involved parties define data acquisition standards collaboratively and feed those standards to CMMS, which is the heart of an E-Maintenance system.

These data collection KPIs include what type of data form what source to collect and for what purpose such data should be collected. Therefore, data volume and number of sources that the data need to be collected from, will be minimized and right data with higher levels of accuracy will be collected. Data collection KPIs can vary based on different customers' business strategies or the industry that customer is active in. For instance, different maintenance strategies such as "producing high quality products" or "reducing the downtime", or different industries such as automotive or food industry, requires different maintenance approaches and therefore, different data need to be collected.

These data collection KPIs and standards also mean transparent definition of what data quality means for all involved parties, inside and outside of their organizations. Therefore, all involved stakeholders should have a common and enterprise-wide understanding towards data quality. Moreover, all stakeholders should commit regarding collecting high-quality data, so that high-quality data are collected right from the relevant sources. Since sensors and other e-technologies, used for data acquisition are less error-prone compared to human, data collection should be more automated.

Once data is collected from subjective and objective sources, E-Maintenance service provider or the party in charge of data collection, compares acquired data with pre-defined data collection KPIs. If collected data from different sources fit data acquisition standards, then it can be assured that the collected data is adequate and relevant for the purpose of data collection. If not, then more data or maybe even data from other or new sources need to be collected. This checkpoint smoothens the information flow and prevents waste actions such as data pre-processing

Collected condition monitoring data can be considered as a new business and a source of revenue. Companies can purely offer data collection and data analysis as a service to assets owners and other third parties without offering associated maintenance actions. As a result, data collection should start by considering data both from IT and business perspective.

Data is further aggregated from different sources and systems (earlier Figure 2), but before starting the data analysis, the quality of data needs to be approved. Data quality checks whether or not, collected data is "Fit-for-Use" Should the data be messy or noisy, data cleaning actions should be carried out as soon as possible and collaboratively with other stakeholders. In this way, all involved parties are aware of what data has been eliminated or what actions have been done for cleaning noisy and dirty data.

If the quality of acquired data has met the data collection KPIs and fits the aim of data collection, data processing takes place, aiming at converting the data into information and preparing for maintenance decision-making. After data has been analyzed, the obtained information is visualized. But prior to sharing information to right stakeholders and other decision-makers, data unification and interoperability should be checked. Data Unification focuses on solving interoperability, data conversion challenges and standardizing data formats within an E-Maintenance system. Since data is being shared among different organizations, the role and the type of information system may vary from each party to others. Therefore Data Unification requires commitment and effort from all E-Maintenance stakeholders in order to establish compatible information systems not only with other involving parties but also within their own organizations by using web-technologies and cloud-computing

Cloud computing and Web technologies, facilitate not only sharing data and information, but also infrastructures like networks, servers and services by applying same maintenance-related tools. In case the data is in a wrong format, the data format should be unified before sharing with other actors. Data Unification focuses on solving interoperability and data conversion challenges and standardize data formats like Extensive Markup Language (XML) within E-Maintenance system, so that all stakeholders can easily share data and information, interpret the data accurately and in a right context, and as a result have a common understanding over the exchanged data. Therefore, when all stakeholders make their information systems consistent and adaptable, use enabling technologies as well as standard and identical data formats, they can share data easily and seamlessly to right actors, apart from their locations and make right decisions.

After data has been shared with right parties, the maintenance-related decisions (e.g. ordering spare parts, fixing the asset, etc.) are made. These decisions are then sent and documented in CMMS as a Decision Support System (DSS). CMMS schedules maintenance actions, while considering several factors such as criticality of customers and availability of workforce or spare parts. Maintenance technicians on customers' site can download the maintenance schedules via their mobile devices. Finally, after technicians have performed the maintenance actions, they document maintenance actions on CMMS and update asset's maintenance history via their mobile devices.

*Scientific implications*

The scientific implications of this study include providing new contribution to E-Maintenance and the different perspectives covered by the previous literature (Aboelmaged 2015, Iung *et al.,* 2009, Muller *et al.,* 2008, Levrat *et al.,* 2008, Bangemann *et al.,* 2006) by highlighting the deficiencies of the discussion surrounding the perspectives of data management in E-Maintenance. On the contrary of (Aboelmaged 2015, Campos 2014, Jantunen *et al.,* 2010) who have studied E-Maintenance from technological, economical or managerial views, this study identifies the most common data management challenges in E-Maintenance systems. Unlike (Campos et. *al.,* 2016, Murthy *et al.,* 2015, Aljumaili *et al.,* 2015, Tretten and Karim, 2014, Candell *et al.,* 2009) who discuss specific data management issues in the context of E-Maintenance, this research has studied all common data management challenges and listed different types of data which need to be acquired in E-Maintenance systems. Additionally, In line with Wan *et al.,* (2017), the role of close collaboration among all involved stakeholders in E-Maintenance has been highlighted in this study.

*Managerial implications*

Managerial implications include emphasizing how understanding the E-Maintenance related challenges helps maintenance managers and other involved stakeholders in E-Maintenance systems to better solve the challenges. These findings, based on the practices of an E-Maintenance industry leader, and validating the data management challenges presented in the literature, provide managers confidence to develop the activities in their companies. Thanks to Process Activity Mapping, the proposed future state of E-Maintenance may provide food for thought for practitioners to understand the big picture over E-Maintenance and to develop their practices. Overall, the findings can be utilized by maintenance managers as a practical way of overcoming data management challenges in E-Maintenance.

## 6. Conclusion

Data management challenges in E-Maintenance have been studied with narrow focus to data and appear as one of the less-studied topics in the literature. Hence, this paper further analyzes data management challenges in E-Maintenance systems and propose a conceptual approach to address identified challenges in practice. The study is realized as a combination of a literature review and by the means of analyzing the practices on an industry leader. The identified data management challenges that relate to E-Maintenance systems and their associated proposed solutions are summarized.

Analyzing the practices of the industry leader allowed mapping the current state of E-Maintenance systems. The study revealed that although the analyzed company is an industry-leader in offering

maintenance services, E-Maintenance is not fully implemented in practice and more remote maintenance than the use of an actual E-Maintenance system may take place. Underlying data management challenges were identified and an improved state was proposed.

The study provides understanding over E-Maintenance by bringing together relevant aspects that are typically addressed in a more dispersed manner. However, since the study is based on analyzing the practices of a single company and the supporting documentation, the generalizability of the results may be limited, and the proposed approach might have limitations in suitability for use in other companies or industries. Also, the study provided a general understanding over data management challenges in E-Maintenance which was based on qualitative methods, including interviews and reviewing company confidential materials, potentially posing some further limitations. Therefore, in order to strengthen the findings, future research topics can focus on each of mentioned data management challenges more deeply. Future research include further validating the presented model by analyzing its applicability in other companies and industries. Considering how to balance internal and external data usage, and the use of quantitative methods, such as data mining for analyzing maintenance data from different perspectives and converting data into knowledge are also encouraged.

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