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Lasse Metso

## INFORMATION-BASED INDUSTRIAL MAINTENANCE – AN ECOSYSTEM PERSPECTIVE

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Lasse Metso

## **INFORMATION-BASED INDUSTRIAL MAINTENANCE – AN ECOSYSTEM PERSPECTIVE**

Thesis for the degree of Doctor of Science (Technology) to be presented with  
due permission for public examination and criticism in the Auditorium of the  
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Finland on the 14<sup>th</sup> of December, 2018, at noon.

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**Supervisors** Professor Timo Kärri  
LUT School of Engineering Science  
Lappeenranta University of Technology  
Finland

Associate professor, Docent Ville Ojanen  
LUT School of Engineering Science  
Lappeenranta University of Technology  
Finland

**Reviewers** Professor Ramin Karim  
Division of Operation and Maintenance Engineering  
University of Luleå  
Sweden

Associate Professor Jaime Campos  
Department of Informatics  
Linnaeus University  
Sweden

**Opponent** Professor Hannu Kärkkäinen  
Industrial and Information Management  
Tampere University of Technology  
Finland

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# **Abstract**

**Lasse Metso**

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In industrial maintenance, the increasing amount of data and information makes the management of information flows much more challenging than previously. Data from different sources is another issue, data can be real-time data from sensors or from different software systems. The type of data can vary from structured data to unstructured data. The Internet of Things (IoT) and modern information and communication technology make it possible to collect data easily. The problem is to recognize the relevant data to support the decision-making process and sharing data and information to right parties in right time.

The aim of this thesis is to identify problems and benefits in information management in industrial maintenance. After the identification of problems and benefits, it is possible to create models and methods for improving the management of information in the industrial maintenance ecosystem. The qualitative research method is used in the empirical part of thesis. Surveys and interviews are used in the qualitative data collection.

The thesis concerns the research gap in identifying problems and benefits in information management in the industrial maintenance ecosystem systemically. The need to share data and information has increased significantly in the networked maintenance ecosystem. The key aspects in information management in maintenance are: why, with whom, what, and how to share data. The thesis offers three main solutions to issues in information management in the maintenance ecosystem. First, the SHELO model was developed and tested in this study. It can be used to find the strengths and weaknesses in maintenance and in the maintenance service network. Second, data sharing is found to improve decision making in maintenance by offering the needed information combined from different sources. Thirdly, the findings highlight the importance of the whole maintenance ecosystem in developing maintenance quality.

Keywords: industrial maintenance, information management, intelligent maintenance, data sharing, SHELO, industrial network, ecosystem



## Acknowledgements

Finally, this book is done. While writing articles and the introduction, I had several ups and downs, and I could not have succeed without help from people around me. Now it is time to express my gratitude to the people who have supported me during this work.

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December 2018  
Lappeenranta, Finland

Lasse Metso



*“Never give up! “*

Valtteri Bottas, Azerbaijan Grand Prix, 2017

*“Just leave me alone; I know what I'm doing”*

Kimi Räikkönen, Abu Dhabi Grand Prix, 2012



# Contents

## Abstract

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## List of publications

The thesis is based on the following scientific publications. The rights have been granted by the publishers to include the articles in a doctoral dissertation.

- I. Metso, L. (2013) Information gaps and lack of competence in maintenance, Conference article. In *Proceedings of Maintenance Performance Measurement and Maintenance*, 12th-13th September 2013 Lappeenranta, FINLAND, <http://urn.fi/URN:ISBN:978-952-265-443-4>, pp 249-259.

Sole author of the paper. The author had primary responsibility for revising the paper during a peer review process. The paper was accepted based on a double-blind review of the full paper.

- II. Metso, L., Marttonen, S., Thenent, N., and Newnes L. (2016), Adapting the SHEL model in investigating industrial maintenance, *Journal of Quality in Maintenance Engineering*, Volume 22, Issue 1, pp. 62-80.

The author was responsible for conducting the literature review, doing the analyses, drawing the conclusions, and writing the article. The co-authors were involved in designing the research, creating the idea for research and the writing process. The author had primary responsibility for revising the paper during a peer review process. The paper was accepted based on a double-blind review of the full paper.

- III. Metso, L., Marttonen-Arola, S., Ali-Marttila, M., Kinnunen, S-K, and Kärri, T. (2016), Identifying fleet data sharing needs, problems and benefits with the Shelo model, Conference article. In *Proceedings of Maintenance Performance Measurement and Maintenance*, 28th November 2016, Luleå, SWEDEN. pp. 149–163. Available at: <http://ltu.diva-portal.org/smash/record.jsf?pid=diva2%3A1081252&dswid=8751>.

The author was responsible for conducting the literature review, doing the analyses, drawing the conclusions, and writing the article. The co-authors were involved in data collection and the writing process. The author had primary responsibility for revising the paper during a peer review process. The paper was accepted based on a double-blind review of the full paper.

- IV. Metso, L., and Kans, M. (2017), An ecosystem perspective on asset management information, *Management Systems in Production Engineering*, Volume 25, Issue 3, paper 22, pp 150-157.

The author was responsible for conducting the literature review, doing the analyses, drawing the conclusions, and writing the article. The co-author was involved in the same tasks as the author, with similar contribution. The author had primary responsibility for revising the paper during a peer review process. The paper was accepted based on a double-blind review of the full paper.

- V. Metso, L., Baglee, D., and Marttonen-Arola, S. (2018), Maintenance as a combination of intelligent IT systems and strategies: a literature review, *Management and Production Engineering Review*, Vol. 9, Number 1, 2018.

The author was responsible for conducting the literature review, doing the analyses, drawing the conclusions, and writing the article. The co-authors were involved in designing the research, creating the idea for research and the writing process. The author had primary responsibility for revising the paper during a peer review process. The paper was accepted based on a double-blind review of the full paper.

## Nomenclature

### Abbreviations

AaaS	Assets as a Service
CBM	Condition-based maintenance
CMMS	Computerized Maintenance Management Systems
CPS	Cyber-Physical Systems
ERP	Enterprise Resource Planning
FMEA	Failure Mode and Effects Analysis
FTA	Fault Tree Analysis
GPS	Global Positioning System
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
ICT	Information and Communication Technologies
IoT	Internet of Things
IT	Information Technology
JAMK	Jyväskylä University of Applied Sciences
PDA	Personal Digital Assistant
PdM	Predictive maintenance
RCM	Reliability-centered maintenance
RFID	Radio-frequency identification
SCM	Supply Chain Management



# 1 Introduction

## 1.1 Background and motivation

In industrial maintenance, one of the key problems is managing the increasing information flow and system complexity. The amount of digital product information and other data from equipment manufactures and other sources is increasing rapidly (Candell et al., 2009).

Big data and the Internet of Things (IoT) have increased the amount of data on maintenance exceedingly. Big data is a term describing high-volume, high-velocity, complex and variable data that demand advanced techniques and technologies to capture, storage, distribute, manage, and analyse information (Gartner, 2015; Gandomi and Haider, 2015). IoT integrates the virtual world of information technology (IT) with the real world (Uckelmann et al., 2011). IoT uses Internet protocols to connect machines, equipment, software, and things in surroundings without human intervention (Said and Masud, 2013). IoT is more than a support for the supply network; IoT should be understood as a business ecosystem (Rong et al., 2015).

IoT increase the amount of data in maintenance, as also complexity increases in outsourced maintenance, and the networking trend with the huge amount of data can add problems with fragmented data due to lack of communication between people, organizations and technological systems (Wang et al., 2013; Candell et al., 2009; Ranasinghe et al., 2011). There are a lot of software products in industrial maintenance, and information sharing and communicating between different parties is difficult (Candell et al., 2009). The integration of maintenance systems to organizations' IT systems is important in the decision-making process (Swanson, 2003; Crespo Marquez and Gupta, 2006). This study highlights the importance of data and information in the information-based maintenance ecosystem. Maintenance ecosystem can include maintenance internal or external partners (Pintelon & Parodi-Herz, 2008) such as OEMs, dealers, and service providers and software systems, e.g. CMMS, asset management systems, eMaintenance systems and of course in-house maintenance organization.

The maintenance playground is fragmented, it has a large number of actors, and they have their own software systems which do not work together (Candell et al., 2009; Ranasinghe et al., 2011). The different systems reduce companies' possibilities and motivation to define a common platform. Shared big data can create new value by intensive and creative use of relevant data, resulting for instance in the optimization of maintenance and operations, and prolonged asset lifetime. The service provider can for example give support to decision makers by collecting high quality data from several sources, identifying similarities in the data and creating new and better analysis based on the combined data.

Data collection, management, access, and dissemination practises have an effect on the quality of data. Data quality is often understood to mean accuracy, but information quality is a much wider concept (Dawes, 2012). For example, Kahn et al. (2002) have presented a model for describing the dimensions of information quality:

- Sound information: Free-of-error, concise representation, completeness, and consistent representation
- Useful information: Appropriate amount, relevancy, understandability, interpretability, and objectivity
- Dependable information: Timelines and security
- Usable information: Believability, accessibility, ease of manipulation, reputation, and value-added.

Information gaps or lack of competence can cause serious problems in maintenance (Thenent et al., 2013; Metso et al., 2016). The data is not shared smoothly between companies, but there can be challenges in transferring the data even inside a single company as well. In order to utilize the data in the maintenance ecosystem, the challenges related to data sharing need to be identified and solved in maintenance as well as in general.

It is important to know the information flows needed in maintenance actions when implementing a new information system. Computerized Maintenance Management Systems (CMMS) are widely used in companies, and new-generation systems are gaining ground, e.g. eMaintenance, Industry 4.0 and Maintenance 4.0, where data is collected from different sources and new intelligent sensors and equipment are networked. eMaintenance is described as a tool for integrating companies' production and maintenance operations through information-technological solutions (Crespo-Marquez and Gupta, 2006; Garg and Desmukh, 2006; Jardine et al., 2006; Levrat et al., 2008; Muller et al., 2008A; Aboelmaged, 2015). Jantunen et al. (2017) describes eMaintenance as a philosophy supporting the move from "fail and fix" to "predict and prevent" strategies. Industry 4.0 makes predictive manufacturing possible, the trend is smart manufacturing leading to industrial big data environments (Lee et al. 2014). Maintenance 4.0 is a self-learning and smart system that predicts failures, makes diagnoses and triggers maintenance by using IoT (Kans et al., 2016). Industry 4.0 enables asset management with real-time data.

This thesis focuses on the research gaps in information management in industrial maintenance. However, big data and increasing data flows are investigated (e.g. Candell et al., 2009; Ranasinghe et al., 2011), as well as the complexity in maintenance networks (e.g. Cousins et al., 2008). Identifying problems and benefits in information management in industrial maintenance systematically has not been done previously, and data sharing has not been studied thoroughly enough in the maintenance ecosystem.

## 1.2 Objectives and scope

The main objective to this thesis is to identify and categorize information management challenges and benefits in the maintenance ecosystem to develop information sharing and to improve the maintenance information process by better information management. Figure 1 presents the linkage between the objectives, research questions and individual publications of this thesis.

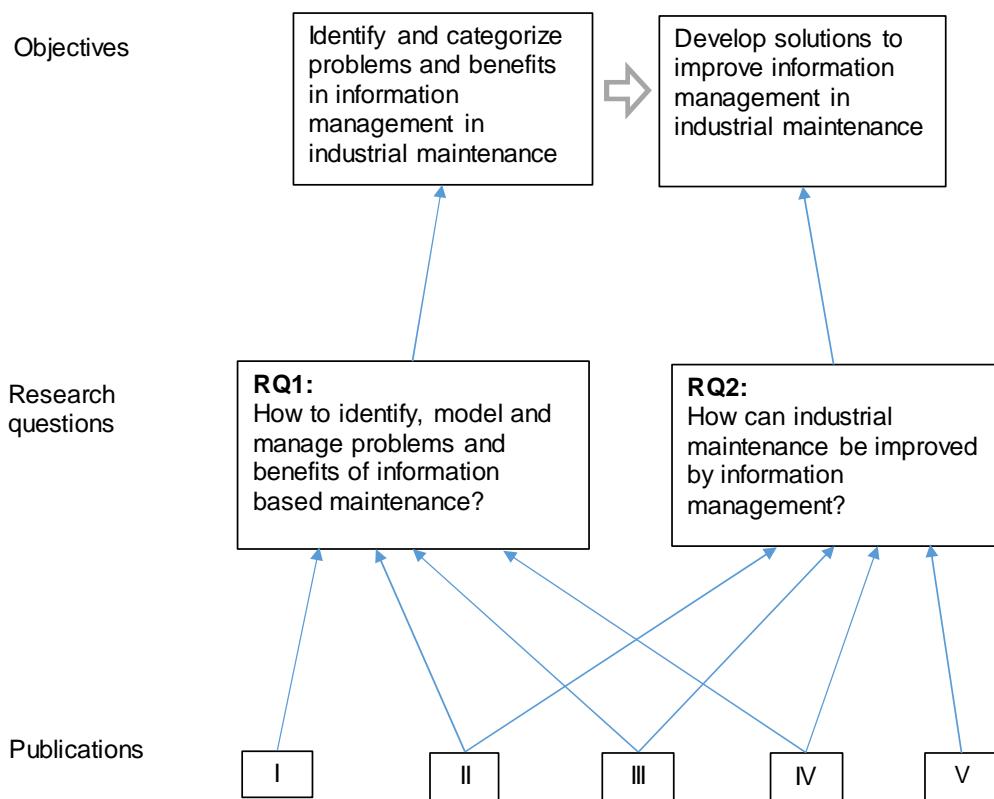


Figure 1. Objectives, research questions and publications

The objectives are divided into two research questions. Research question 1 focuses on how to identify, model and classify the problems and benefits in industrial maintenance. Publications I - IV concern the problems and benefits in maintenance information management.

The second objective aims at developing solutions to improve maintenance information management. Research question 2 concerns how industrial maintenance can be improved by information management. Publications II - V offer answers to this question.

Figure 2 presents the scope of the thesis. Information management in the maintenance ecosystem is in the intersection of two large research areas: industrial asset management and information management. These research areas present a combination of maintenance information management. This thesis aims at presenting these two research traditions. The thesis has a maintenance managerial viewpoint, as the aim is to develop maintenance actions by information management.

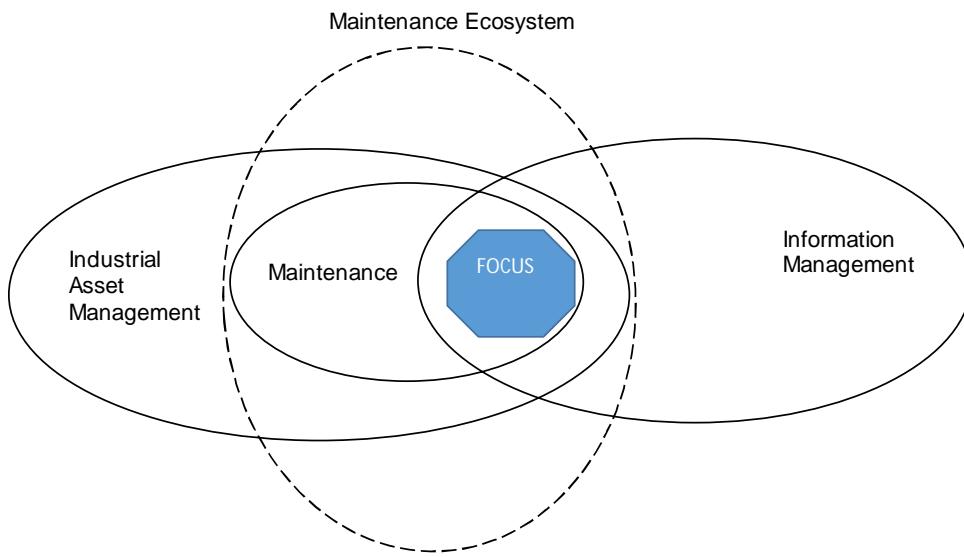


Figure 2. Scope of the research.

This study started first by focusing on information management in industrial maintenance. Then the researcher noticed that in information management in maintenance there was a need to use information from other sources than just from maintenance software systems and equipment manuals, so asset information systems and the maintenance ecosystem with information sharing both inside a company and wider in the whole ecosystem were added to the research focus. This was done because there was a need to discuss asset information management in life-cycle and inter-organization processes.

Maintenance management is facing changes with the emergence of IoT (Wang et al. 2013). These changes include an increase in information flow, which means developing more complex and technologically advanced information systems. The networking trend and the huge amount of data can add problems with fragmented data due to lack of communication between people, organizations and the technological system (Candell et al., 2009; Ranasinghe et al., 2011)

It can be a problem for service providers in industrial maintenance to manage the ever-increasing information flow and system complexity. An increasing amount of

information provided with hardware and software products from manufacturers, subsystem suppliers and other sources is available (Candell et al., 2009). Attempts to resolve the challenges related to information sharing and communication between different parties in industrial maintenance include the implementation of advanced software solutions, such as Product Lifecycle Management Systems (Lee and Wang, 2008) and eMaintenance (Candell et al., 2009). However, as recognised by O'Dell et al., (1998), while software helps in information collecting and sharing, it does not solve all problems. It is important to identify the barriers and benefits of sharing data. Data sharing can lead to better decision-making processes and gaining competitive advantage.

### 1.3 Key concepts in maintenance information management

Data, information and knowledge are terms used in spoken Finnish language almost as synonyms. However, data, information and knowledge are not interchangeable concepts.

**Data** is a set of discrete facts about events. Data is described as structured records of transactions. Data describes only a part of what happened, and it tells nothing about its own importance or irrelevance. (Davenport and Prusak, 1998)

**Information** is described as a message, which has a sender and a receiver. Information must have an impact – information is data that makes a difference. The receiver decides whether the message is really information for him. A document full of unconnected ramblings may be considered “information” but judged to be noise by the recipient. Data is transformed into information by adding value:

- Contextualized: we know why the data was gathered
- Categorized: we know the units of analysis and key components of the data
- Calculated: the data has been analysed
- Corrected: errors have been removed from the data
- Condensed: the data may have been summarized in a more concise form.

Computers can help to add value and transform data into information, but they can rarely help with the context. Humans work with categorization, calculation and condensing. (Davenport and Prusak, 1998)

**Knowledge** has been seen as broader, deeper and richer than data and information. Davenport and Prusak (1998, p.5) define knowledge as follows:

*“Knowledge is a fluid mix of framed experience, values, contextual information, and expert insight that provides a framework for evaluating and incorporating new experiences and information. It originates and is applied in the minds of knowers. In*

*organizations, it often becomes embedded not only in documents or repositories but also in organizational routines, processes, practices, and norms.”*

Knowledge is derived from information as information is derived from data. Data can be found in records or transactions, information in messages, and knowledge can be obtained from individuals or groups of knowers, or sometimes in organizational routines. (Davenport and Prusak, 1998)

Knowledge can be categorized into explicit or tacit knowledge. Explicit knowledge can be understood as knowledge or information that can be put in a tangible form. Tacit information or knowledge is difficult to transfer because it is difficult to define the nature of tacit knowledge. It is some kind of know-how or it is deeply rooted in action, and it can be found in the minds of humans. (Nonaka and Takeuchi, 1995)

In the maintenance context, the allocation to data-information-knowledge is not so clear than in definitions in information management. Information is important for meeting maintenance management objectives (Fernandez et al., 2003). Maintenance information management is often described as a part of a maintenance information system (Garg and Deshmukh, 2006). For example, Galar et al. (2012) present an idea that maintenance information is extracted by processing with data analytic tools. The CMMS software collects and analyses data but seldom gives decision analysis that managers can trust (Labib, 1998). However, data quality can be improved by auditing, benchmarking and using improvement recommendations created by maintenance staff (Olsson et al., 2010). However, eMaintenance systems are described as an intelligent centre which can offer support to decision making (Iung and Crespo-Marquez, 2006; Iung, 2003).

In this thesis, data is understood as a set of facts usually stored in a computer with proper software. Information is seen as data with an impact. However, in real life it is difficult to separate data and information in context of industrial maintenance, and in this thesis data and information are used almost as synonym. Explicit knowledge is considered in the information management sections, but tacit knowledge has been left out.

The traditional view of value creation is a stream or a chain, where the actors interact by refining input, raw material and labour to come out in the form of finished products. In reality, the situation is often more complex than that because of outsourcing and third party collaborating connected by networks (Cousins et al., 2008). According to Moore (1993), a business ecosystem is an economic community consisting of interacting organizations and individuals, which are the organisms of the business world. The ecosystems create value for the customers in the form of goods and services.

Assets are entities that bring potential or actual value to an organization (ISO 55000, 2014). The value varies with the context, organization and situation, and it could be tangible or intangible, as well as financial or non-financial. Asset management can be described as a set of activities for reaching a given business or organizational objective (Hastings, 2010), including identifying the required assets and funding, acquiring the

assets, providing logistics and support to maintenance, and disposing of or renewing the assets.

## 1.4 Outline of the thesis

This thesis consists of two parts. The first part provides an introduction and an overview of the research, the theoretical foundations, the research methods, the research contribution, and a conclusion. The original publications are included in the second part of the thesis, following the order presented in the list of original publications. The introductory part is divided into five chapters, which can be seen in Figure 3. The first chapter presents the background, objectives and scope of the thesis. The research questions are formulated in the first chapter. The second chapter presents previous literature about information management in the area of asset management and the maintenance ecosystem. The third chapter provides the methodological justification of the thesis by introducing the theoretical perspective, methodologies and data used in the research. The fourth chapter summarizes the main findings of individual publications to present the results of this thesis and answer the research questions defined in the first chapter. The fifth chapter concludes the thesis by presenting the theoretical contributions, managerial implications and future research prospects. Also, the reliability and validity of the research is evaluated in chapter 5.

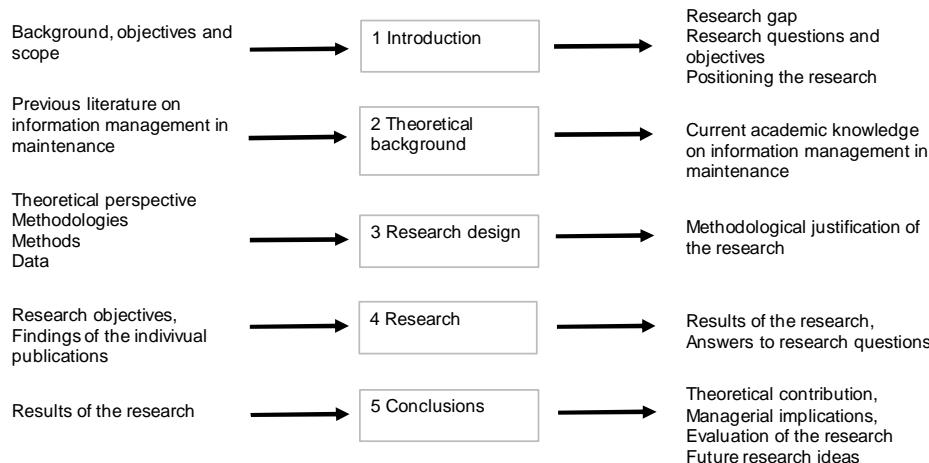


Figure 3. Outline of the research.



## 2 Theoretical background

This chapter presents first industrial asset management, and then information-based maintenance which needs data sharing with other systems and parties. The SHEL model in maintenance is described as a tool to identify weaknesses and strengths in developing industrial maintenance.

### 2.1 Industrial asset management

Asset management standards and processes within physical asset management and the industrial maintenance ecosystem are presented below.

ISO 55000 (2014) provides an overview of asset management and asset management systems as follows: “*Asset management translates the organization’s objectives into asset-related decisions, plans and activities, using a risk based approach.*” The benefits of asset management can be e.g. improved financial performance, informed asset investment decisions, managed risk, improved services and outputs, demonstrated social responsibility, demonstrated compliance, enhanced reputation, improved organizational sustainability, and improved efficiency and effectiveness. Asset management pays attention to categories of asset types; physical, human, information, financial, and intangible ones (PAS 55-1, 2008).

ISO 55000, ISO 55001 and ISO 55002 can be used to create asset type -specific management standards or technical specifications in any relevant sectors. ISO 55001 (2014) defines asset management systems requirements and ISO 55002 (2014) gives guidelines on how to implement ISO 55001.

Ojanen et al. (2012) noticed that the research has focused on the early phases of the life cycle, planning, design and development phases, and less on operations, maintenance and later stages. This is natural, because the early stages influence the later parts in the life cycle, for example maintainability. However, a lot of research has focus on maintenance (e.g. Jardine et al., 2006; Candell et al., 2009; Tsang, 2002). Research to develop collaboration in the field of asset and maintenance management has been done (see e.g. Emmanouilidis et al., 2009; Spires, 1996) The collaborative relationships between industrial service providers and customers in industrial maintenance are essential. Collaborative maintenance takes the customer value perspective strongly into account in the development of maintenance services. An increasing number of studies has focused on the management and development of industrial services (e.g. Ojasalo, 2007; Barry and Terry, 2008; Panesar and Marakeset, 2008). However, studies on collaborative maintenance management are relatively few in number (Ojanen et al., 2012). On the other hand, maintenance can be seen as a “cooperative partnership”, due to the change from the role of an inevitable part of production to an essential part of the whole while maintenance management is a complex function in which technical and management skills are needed (Pintelon and Parodi-Hertz, 2008).

A fleet is understood as a group of production lines or a set of assets that share some characteristics that group them together (Medina-Oliva et al., 2014). Companies have a view only on the fleet of assets they own. However, a manufacturer or an equipment provider has knowledge of their products but the data and information is partly fragmented to the customers who have purchased the assets. Therefore, the equipment provider has rarely access to all data of the fleet of assets that they have produced. Instead of just considering assets as singular objects, considering them as a fleet can generate certain benefits, such as fault detection, resource optimization, and product or service development (Kinnunen et al., 2016, Kortelainen et al., 2016).

According to Frånlund (2016) physical asset management involves collaboration between a number of functions and processes within the company in order to achieve having right systems and facilities for company activities, ensuring desirable operation, and implementing profitable maintenance. The inner circle (asset requirements, design, manufacturing, etc.) describes the life-cycle of physical assets. The “clue” to connecting and controlling functions, activities, operations, and life-cycle phases of assets is the asset management information system (more about this in chapter 2.2). Physical asset management involves collaboration of functions and processes in order to have the right system and facilities for the company, to ensure desirable operation, and to implement profitable maintenance (see Figure 4).

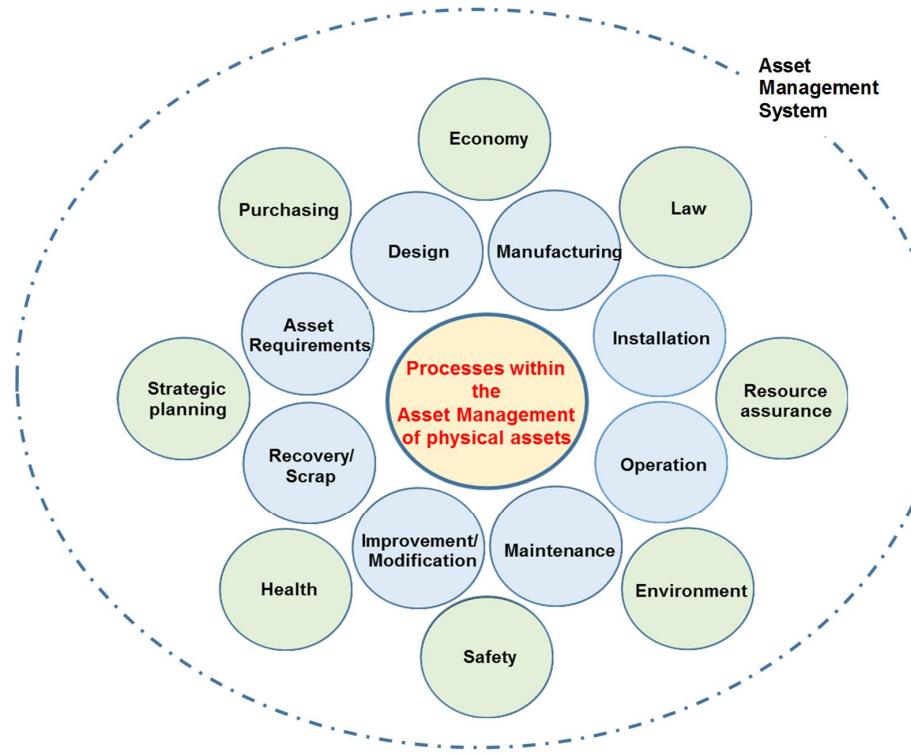


Figure 4. Physical asset management and information system (modified from Frånlund, 2016).

Value creation is often described as a stream or a chain where actors input e.g. raw material, and the output is finished products. Value creation can be also used in service creation. However, in reality this is more complex because of outsourcing and n-party collaboration connect players to each other in a star-like form or in a network (Cousins et al., 2008). A business ecosystem consists of interacting organizations and individuals, which together build up an economic community (Moore, 1993). A business ecosystem is not stable, new actors might enter and some old actors leave. Business ecology can have different meanings for different actors, some actors may be in the centre and others in the outer edge of the circle (Olve et al., 2013). In a technology-driven business ecosystem the required data comes from different data sources, e.g. environmental data, performance data, condition monitoring data, production data, and so on. New technology can cause problems to maintenance if these are not paid attention to. In industrial maintenance the network service provider has to interact with other actors in the maintenance ecosystem, and cooperation with the suppliers of surrounding systems is needed to reach the necessary information (Kans and Ingwald, 2016).

The number of actors has increased in ecosystems, the example in Figure 5 below is from the Swedish railway industry. The environment is complex from technical, organizational and operational aspects. In maintenance the main problems have been information handling and management, regulation and control, as well as lack of resources. The actors have sub-optimized their own tasks instead of cooperating. The existing asset information model is presented in Figure 5. (Ingwald and Kans, 2016)

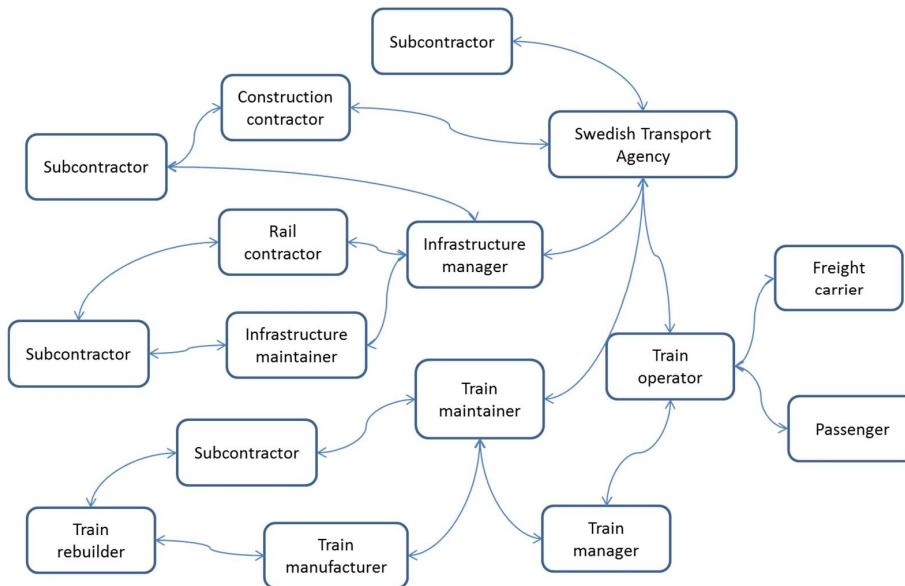


Figure 5. Existing asset management model in the Swedish railway (modified from Ingwald and Kans, 2016).

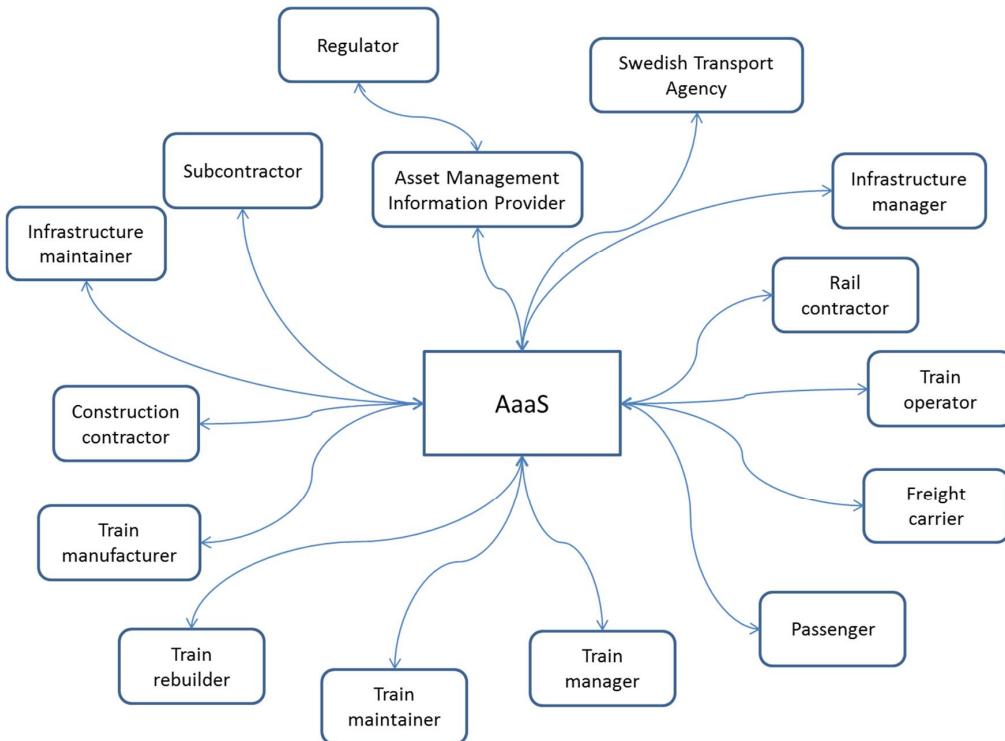


Figure 6. AaaS asset information management model (Metso and Kans, 2017).

The Assets as a Service (AaaS) model presented in Figure 6 allows smooth information flows to all actors, which improves information handling and management. Data and (/or) information are organized by the Asset Service Provider, as well as which data is shared and with whom it is shared. Data is shared with several actors and it is always available in the right format and distribution form. (Metso and Kans, 2017)

## 2.2 Information-based industrial maintenance

Asset management can be described as a set of activities for reaching business or organizational objectives (Hastings, 2010). An organization specifies the internal and external communication relevant with respect to the assets, asset management and asset management system: what, when, to whom, and how to communicate (ISO 55000, 2014). An asset management information system is designed to create and maintain the

documentation of asset management functions (Hastings, 2010). Asset management information systems are used to identify equipment, locations and activities. These systems are known as CMMSSs. Figure 7 shows the main components of the asset management information system defined as corresponding with the information requirements for the asset (Kans and Ingwald, 2012).



Figure 7. Asset management information system (Hastings, 2010).

Maintenance is defined for activities to retain or to restore an item to a specific state. Maintenance is scheduled for a short period of time, it requires planning, work preparation and enough maintenance capacity. (Dekker, 1996) Maintenance can be divided into corrective maintenance and preventive maintenance, see Figure 8. Corrective maintenance focuses on the functionality of the item, and it has actions such as failure detection, failure localization, failure correction, and function checkout. Corrective maintenance is the reparation of an item and it is usually unplanned and unscheduled. In corrective maintenance, also called breakdown maintenance, maintenance actions are taken after problems, e.g. breakdowns in production, while preventive maintenance tries to prevent abnormal function before abnormality occurs (Shin and Jun, 2015). Preventive maintenance is planned to be done in a stated time interval. Preventive maintenance tests all functions and tries to find hidden failures. It reduces wear-out failures and tries to increase the useful life of an item. Preventive maintenance can be divided to predetermined maintenance and predictive maintenance. Predetermined maintenance is scheduled and based on a fixed time schedule for inspect, repair, and overhaul. Predictive maintenance is based on condition-based maintenance (CBM) diagnostics (current condition) or prognostics (forecasting of remaining equipment life) (Birolini, 2002; Verma et al. 2010; Niu et al., 2010).

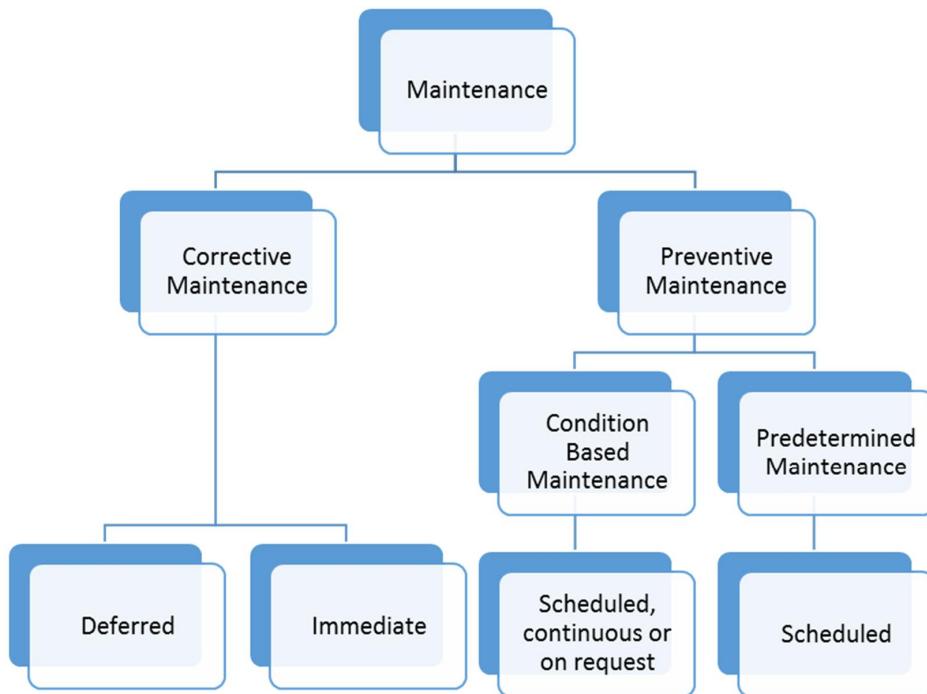


Figure 8. Maintenance approaches (Niu et al., 2010, p. 787)

In CBM maintenance, the decisions are based on information collected through condition monitoring. Information-based CBM steps in maintenance decision making are presented in Figure 9. In the data acquisition step, all relevant information is collected to obtain system health. Information is handled and analysed in the data processing step. Maintenance decisions are made after these steps. Condition monitoring data can be for example vibration data, oil analysis data, pressure, temperature, humidity, moisture, and environmental data, weather data or acoustic data. (Jardine et al., 2006)

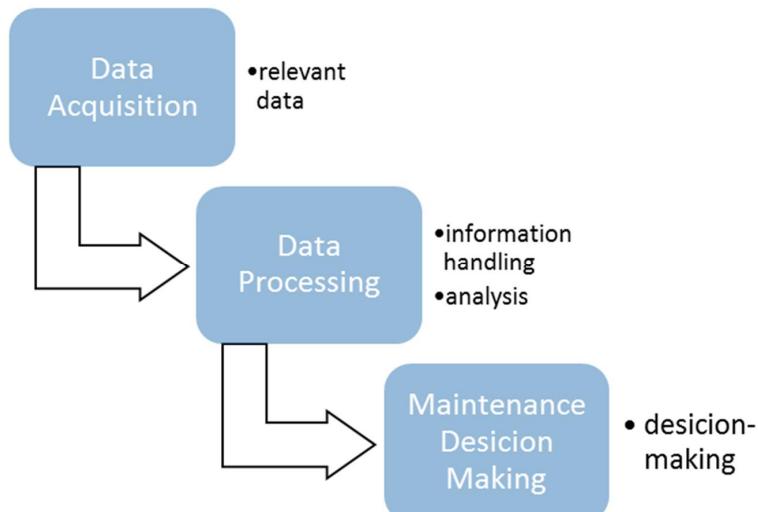


Figure 9. Information-based decision steps in maintenance (adapted from Jardine et al., 2006).

ICT enables everybody to collect and analyse maintenance and production data to create improvement in manufacturing costs, safety, environmental impact, and equipment reliability. This approach to maintenance is called eMaintenance. eMaintenance is a distributed intelligent and integrated system (Pétin et al., 1998). The strength of maintenance connections to other systems is in using various data sources and different tools and techniques (Baglee and Knowles, 2012). The “Intelligent Maintenance Centre” describes eMaintenance because it supports the use of data collection, data analytics and transfer to remote use (Iung and Crespo-Marquez, 2006).

eMaintenance is a strategy within maintenance supported by the use of ICT and new technologies. It utilizes real-time data from different sources to provide support to decision makers (Tsang, 2002).

Cyber-Physical Systems (CPS) connect physical assets with sensors, data acquisition systems and computer networks to networked machines. These sensors and intelligent machines generate data known as Big Data continuously. This manufacturing industry trend is called Industry 4.0. The implementation of Industry 4.0 manufacturing systems aims at better production quality and system reliability with intelligent networked machines. (Lee et al., 2015)

## 2.3 Data sharing and open data

The data requirements are different in different organizations. The organization has to consider the risks, roles and responsibilities, as well as the processes, procedures and activities in asset management, information exchange, as well as the quality and availability of information in the decision-making processes (ISO 55000, 2014). Information in asset management activities includes subjects like data management, condition monitoring, risk management, quality management, environmental management, etc. (ISO 55002, 2014).

The organization specifies the requirements and the quality requirements of information in asset management, and the key point is how to communicate with employees, suppliers and contracted service providers (ISO 55000, 2014), contrary to the Open Data concept in which governmental data is available to anyone in any form without copyright restrictions (Murray-Rust, 2008).

A sharper definition of Open Data is: "Open data is data that can be freely used, shared and built-on by anyone, anywhere, for any purpose" (Knowledge International, 2005). Open Data is freely available, but organizations decide what data is released for public access. The main thing is what data is available and how it is available. If the releasing of Open Data is done wrong, for example all data is released, privacy can become an issue (Chernoff, 2010).

Besides opening governmental data, data sharing has proved to be a good practice in science and technology research. Data sharing makes data-based new questions possible for researchers and advances research and innovations (Wallis et al., 2013; Kim and Stanton, 2012). Janssen et al. (2012) have studied the benefits and barriers of Open Data. The benefits are presented in table 1 and the barriers in table 2. The political and social benefits have been merged because they are difficult to separate. The following benefits are recognized as political and social benefits: transparency, more participation, the creation of trust, access to data, new services, and stimulation of knowledge development. Economic benefits are economic growth, stimulation of competitiveness, innovations, improvement of processes/products/services, new products and services, availability of information, and creation of adding value to the economy. Operational and technical benefits are reuse of data, creation of new data by combining data, validation of data, sustainability of data, and access to external problem-solving capacity. (Metso and Kans, 2017)

Even though the advantages are clear, there are barriers in data sharing. Institutional barriers have been identified: unclear values, no policy for publicizing data, no resources, or no process for dealing with user input. The complexity of handling data includes lack of understanding about the potential of data, no access to original data, no explanation of the meaning of data, information quality, duplication of data, no index on the data, complex data format, and no tools for support. Barriers in use and participation are no time, fees for data, registration to download data, unexpected costs, and lack of

knowledge to handle the data. Barriers regarding legislation are privacy, security, licences and limitation to using data, and agreements. Information and information quality problems are lack of information, lack of accuracy of information, incomplete information, non-valid data, unclear value, too much detailed information, information missing, and similar data stored in different systems yielding different results. Technical level barriers are data not in a well-defined format, absence of standards, no support, poor architecture of data, no standard software, fragmentation, and no systems to publicizing data (Janssen et al., 2012; Saygo and Pardo, 2013).

Table 1. Benefits of Open Data (Janssen et al., 2012)

<b>Benefits</b>	<b>Examples</b>
<b>political and social benefits</b>	transparency, more participation, creation of trust, access to data, new services, stimulation of knowledge development
<b>economic benefits</b>	economic growth, stimulation of competitiveness, new innovations, improvement of processes/products/services, new products and services, availability of information, creation of added value to the economy
<b>operational and technical benefits</b>	reuse of data, creation of new data by combining data, validation of data, sustainability of data, access to external problem-solving capacity

Table 2. Barriers of Open Data (Janssen et al., 2012)

Barriers	Examples
<b>institutional level barriers</b>	unclear values (transparency vs. privacy), no policy for publicizing data, no resources, no process for dealing with user input
<b>task complexity in handling data</b>	lack of understanding the potential of data, no access to original data, no explanation of the meaning of data, information quality, duplication of data, no index on data, the data format and dataset are complex, no tools available for support
<b>the use of open data and participation in the open data process</b>	no time, fees for the data, registration to download data, unexpected costs, lack of knowledge to handle data
<b>legislation</b>	privacy, security, licenses and limitations to use data, agreements
<b>information quality</b>	lack of information, lack of accuracy of information, incomplete information, non-valid data, unclear value, too much information, missing information, similar data stored in different systems yields different results
<b>technical level barriers</b>	the data is not in a well-defined format, absence of standards, no support, poor architecture of data, no standard software, fragmentation, no systems to publicizing data

The basic hypothesis of open data is that more intensive and creative use of data can generate new value. The information is understood as given, used uncritically, and trusted without verification. However, open data could be collected or created for other purposes. Open data has potential value, but also risks for validity, relevance and trust. Open data is context- and time-dependent. Taken out of context, open data loses meaning, relevance and usability. Data collection, management, access, and dissemination practises have an effect on the quality of data. Data quality is often used to mean accuracy, but information quality is a much wider concept. Information quality means in practice how the data fits for use by data consumers, including the dimensions of security, consistency and accuracy, as well as relevancy and understandability (Dawes, 2012; Strong et al., 1997).

## 2.4 SHEL model in maintenance

Reliability engineering has been seen as a development of methods and tools to evaluate and demonstrate reliability, maintainability, availability, and safety of components, equipment and systems (Birolini, 2002). Reliability tools are FTA (Fault Tree Analysis), event tree analysis, FMEA (Failure Mode and Effects Analysis) and Markov models (Verma et al. 2010). Reliability engineering may also involve predictive and preventive maintenance (e.g. reliability-centred maintenance, RCM). Nowlan and Heap (1978) have presented a program called RCM to achieve safety and reliability of equipment at minimum cost. They highlight four types of tasks in maintenance: (1) Inspect equipment before failure, (2) Rework before maximum age of equipment is exceeded, (3) Discard equipment before the maximum permissible age is exceeded, and (4) Inspect equipment to find failures which have not been reported yet. The successful implementation of RCM was expected to increase cost effectiveness, improve machine uptime, and offer greater understanding about the level of risk that the organization is taking.

In complex and networked production systems, reliability is essential. Reliability engineering aims at searching causal links in system elements (for example components, structures, people). (Zio, 2009)

The SHEL model is a framework that can be used to study the interactions between individuals, the systems where they function, and the environment which influences the individuals' activities (Hawkins, 1987). Edwards (1972) has presented the SHEL model which comprises three elements that interact with humans (called Liveware): Software, Hardware and Environment. Edwards named the model after the initials of its elements, Software (S), Hardware (H), Environment (E) and Liveware (L). The S element describes the rules, regulations, orders, laws, and procedures in the execution of tasks. The L element describes the physical size and shape, the fuel requirement, food, oxygen, water, input characteristics (senses), information processing, output characteristics, environmental tolerances, and psychological aspects: biases and mental conditions. The H element stands for tools, material, objects and equipment. The E element represents the environmental context like the temperature, the weather and noise. With the SHEL model, the interactions between individuals, the systems where they function, and the environment that influences the individuals' activities, can be studied (Hawkins, 1987). Originally, the SHEL model was created to the investigation of human interactions (Edwards, 1972). The person-to-person relationship was added by Hawkins and Orlady (1993) and the model was called SHELL. Hawkins studied the relationships between Liveware and Software, Liveware and Hardware, Liveware and Environment and Liveware and Liveware. Chang and Wang (2010) have added the element of organization and call the model SHELLO.

The SHEL model was used first in aviation accident investigations, then it was noticed that some accidents were related to airplane maintenance, and so the model was used in aviation maintenance (Edwards, 1972; Lufthansa Technical Training, 1999; Licu et al., 2007). Later the SHEL model was used in maritime organizations (Chen et al., 2013) and

it has also been used in nuclear power generation to study human factors, team work and organizational effects (Kawano, 1997).

The International Civil Aviation Organization emphasizes the organizational issues in aircraft maintenance (ICAO, 1998). The International Air Transport Association (IATA, 2006) specifies five categories in the accident classification system: human, technical, environmental, organizational, and insufficient data. The same elements can be found in the SHELO model: L, S, E, O, and at present element H can be understood to be related to data. Also in industrial maintenance the organizational issues are highlighted (Chang and Wang, 2010).

In this thesis, the SHEL model is developed into the SHELO model, presented in Chapter 4.



### 3 Research design

Research design is the glue that holds the research phases together (Trochim and Donnelly, 2001). Research can be defined as an activity that contributes to understanding a phenomenon (Kuhn, 1996; Lakatos, 1978). Research design describes the selection of research methods suitable for the research problem. Crotty (1998) describes the key features in research design as follows:

- epistemology
- theoretical perspective
- methodology
- methods

The term research design is widely used, but it can have a different meaning in different contexts. Research design can describe the entire research process, or it can mean only the methodology of studies (Harwell, 2011). In this research, the term research design describes the whole research process.

#### 3.1 Theoretical perspective

The word *ontology* is derived from Greek and it is called a theory of “being”, while epistemology deals with the origin and the character of knowledge, as well as the creation of knowledge, and it is called a theory of knowledge (Furlong and Marsh, 2010; Hirshheim, 1985). ‘How do I understand the object of the research?’ is a question about ontology. Ontology asks questions about the nature of reality. A question of epistemology is ‘how can I find information?’ (Hirsjärvi et al., 2009).

Qualitative research has been divided to four paradigms: positivism, post-positivism, critical theory, and constructivism (Guba and Lincoln, 1994) or to three paradigms: positivist, interpretive and critical (Orlikowski and Baroudi, 1991; Chua, 1986). The research paradigm is also called the theoretical perspective. Research paradigms have been studied in social sciences and natural sciences. Several other classifications for research paradigms have been created (e.g. Habermans, 1973; Burrell and Morgan, 1979). The paradigms are usually classified by the views of reality and knowledge, but other classification criteria exist. In this thesis, the classification of Orlikowski and Baroudi (1991) is used because their classification is related to information systems research.

Orlikowski and Baroudi (1991) have defined three criteria to classify scientific paradigms. The first is “physical and social reality”. The second is “knowledge”, more detailed the nature of knowledge. The third one is “the relationship between theory and practice”. This thesis is based on the interpretivist paradigm, and the other paradigms are positivist and critical. The paradigm classifications are presented in table 3.

Table 3. Paradigm classification (Orlikowski and Baroudi, 1991).

	<b>Positivist</b>	<b>Interpretivist</b>	<b>Critical</b>
<i>Physical and social reality</i>	Objective Stable	Subjective Stable	Subjective Dynamic
<i>Knowledge</i>	Evaluating	Evaluating	Constructing
<i>Relationship between theory and practice</i>	Technical	Phenomenon-related Value-laden	Theory criticizes status quo

Positivist researchers try to find law-like generalizations (Neuman, 2011). Positivists believe that the observations of different researchers of the same problem will generate similar results when using similar research processes and statistical tests in investigating a large sample (Creswell, 2009). The positivist paradigm considers reality to be objective and stable, and this means that the researcher is independent. In the positivist paradigm reality is considered external, objective and independent of social actors, and knowledge is created by objective understanding about the processes in the reality (Orlikowski and Baroudi, 1991; Wahyuni, 2012).

Interpretive researchers try to develop generalizations that are context bound, closely related to the researcher and his or her research methods (Lee and Baskerville, 2003). In interpretivism the meaning of data is determined by the context (Myers, 2013). Interpretive researchers attempt to understand phenomena through meanings given by the people involved (Orlikowski and Baroudi, 1991). The interpretive researcher must understand the terms used by the people being studied, or they will understand any meanings in their studies. The researcher looks at phenomena from the “inside” (Myers, 2013).

Critical researchers presume that social reality is produced by people. They assume that social conditions hinder the achievement of e.g. justice and freedom. People can act to change social and economic circumstances, but critical researchers think that their ability to do it successfully is a consequence of social, cultural and political domination. (Myers, 2013)

The interpretivist paradigm is used in this thesis because the data collected by interviews and surveys were in a form dependent on the context. The researcher must understand the language and the context the people in interviews and in surveys use in order to understand the meaning of the data.

### 3.2 Methodology

The framework for the research methods is usually given in the methodology part of a study. Research methodologies can be classified for instance into quantitative and qualitative methods (e.g. Ahrens and Chapman, 2007).

In qualitative research, a naturalistic approach is used in order to understand context-specific phenomena, where the researcher does not manipulate the phenomenon of interest (Patton, 2001). Defined broadly, qualitative research means research that does not use statistical procedures or other quantification methods (Strauss and Corbin, 1990), but qualitative research produces findings from the real world instead (Patton, 2001). Qualitative researchers try to find understanding and extrapolation to similar situations (Hoepfl, 1997). Interviews and observations are dominant in the interpretivist paradigm (Golafshani, 2003).

Hirsjärvi et al. (2009) have recognized seven typical features of qualitative research:

1. The research is nature-comprehensive data collection and the data is collected in a natural and real situation.
2. Humans are promoted as an instrument of data collection. The researcher trusts his own observations and discussions with humans, and also forms and tests can be used.
3. Inductive analysis is used. The researcher aims at unexpected findings.
4. Qualitative methods are used in data collection, e.g. theme interviews, observations, group interviews, and discursive analysis of documents and texts.
5. The target group is selected as appropriate for the purpose, random samples are not used.
6. The research plan can be modified during the research.
7. Cases are dealt with as unique and the data is analysed according to it.

This research is a qualitative research because items 2 to 7 in the above list are fulfilled. Item number 1 is met only partly because the data was mainly collected by surveys and interviews. The research approach used in this thesis is design science and secondary analysis of qualitative data. Qualitative content analysis focuses on meaning rather than quantification. Table 4 presents the research approach, research methods and empirical data.

Table 4. Research designs of the individual publications.

<b>Publication</b>	<b>Research approach</b>	<b>Research methods</b>	<b>Empirical data</b>
<b>Publication I</b>	Design science	Content analysis	Surveys
<b>Publication II</b>	Design science	Content analysis	Surveys, secondary data
	Secondary analysis of qualitative data	Model building	
<b>Publication III</b>	Design science	Content analysis	Interviews, secondary data
	Secondary analysis of qualitative data	Model building	
<b>Publication IV</b>	Design science	Content analysis	Interviews, secondary data
	Secondary analysis of qualitative data	Model building	
<b>Publication V</b>		Literature review	Databases ISI Web of Science, Scopus, SpringerLink, ScienceDirect, and Google Search.

*Secondary analysis of qualitative data*

Archival research is defined as “an empirical study that uses archival data as the primary source of data applying quantitative methods of analysing these data” (Moers, 2007, p.?). However, Heaton (2008) states that secondary analysis of qualitative data has been made since the mid -1990s. Qualitative data has been re-used as so-called secondary analysis. Secondary analysis:

- can re-use pre-existing qualitative data from previous research
- data can be used to investigate in a new or an additional way or it can be used to verify the results of previous research
- can be re-used self-collected data (Heaton, 2008)

Secondary data is useful to find information to solve a research problem and to understand the research problem better and to explain it. A secondary data source provides information that may have been collected for different purposes. This is why it must be judged if the information can be used in the study. There is more data available than researchers can think of - books, journal articles, online data sources, previous research, etc. Secondary data can:

- answer research questions
- solve some or all research problems
- help to formulate the problem or give more concrete information to the research
- support the selection of research methods
- benchmark the results of research

The advantages of using secondary data is saving time and money, data collected by international organizations and governments is of high quality and reliable, longitudinal studies need historical data, and quite often research questions can be answered by combining information from secondary and primary data. (Ghauri and Gronhaug, 2010)

When secondary data is not available or it cannot answer the research questions, the relevant data must be collected. This data is called primary data. There are several options for collecting primary data: observations, experiments, surveys, and interviews. The main advantages in primary data are that it is collected for a certain purpose. This means that the data is consistent with the research questions and objectives. The main disadvantage of primary data is that it takes a lot of time to collect. (Ghauri and Gronhaug, 2010)

In this study, data was collected first for Paper I, and then it turned out that the data was rich enough for a different kind of analysis. In Paper II the same data was used with analysis of a different kind, and a more precise outcome was achieved. The data for Papers III and IV was collected in project DIMECC S4Fleet by interviews.

*Design science*

Design science can be seen as the basis of problem-solving research (Holmström et al., 2009). As the starting point for a study, the problems should be of the kind where a solution can be found.

Design science research includes various contents, e.g. action science, action research, action innovation research, participatory action research, participatory case study, and academe-industry partnerships (Holmström et al., 2009).

Peffers et al. (2007) present six common activities in design science research based on findings in the literature (Archer, 1984; Takeda et al., 1990; Eekels and Roozenburg, 1991; Nunamaker et al., 1990-91; Walls et al., 1992; Cole et al., 2005; Rossi and Sein, 2003; Hevner et al., 2004):

- Activity 1: Problem identification and motivation. Define the research problem and justify the solution. Needs knowledge to state the problem and recognize the importance of the solution.
- Activity2: Define the objectives for a solution. The objectives should be formulated from the problem.
- Activity 3: Design and development. Create the artefact: construct, model, method, or instantiations.
- Activity 4: Demonstration. Demonstrate the use of the artefact to solve the problem.
- Activity 5: Evaluation. Observe and measure how well the artefact solves the problem. Compare the objectives of the solution to actual observed results. At the end of this activity, researchers can decide to iterate back to activity 3 if needed.
- Activity 6: Communication. Drawn conclusions and publish the results.

Design science research is an application of existing knowledge to solve a problem and learn about it. The results of design science research are concrete solutions to the research problem, and at the same time the academic framework is defined. An artefact which solves the research problem can be a model, a method, a framework, a process, a system, or a physical artefact.

### **3.3 Methods**

#### *Content analysis*

Content analysis is a technique to identify reference models and to estimate parameters from textual data (Luna-Reyes and Andersen, 2003). Content analysis is a systematic research method (Krippendorff, 1980; Downe-Wambolt, 1992). It is used to analyse data, usually textual data. The data is subdivided into categories, and this is called the mechanical approach. When determining what categories are meaningful in terms of asked questions, it is called the interpretative approach. The mechanical and interpretative approaches can be linked. Content analysis can be divided into three main forms: qualitative, quantitative and structural analysis (Brewerton and Millward, 2001).

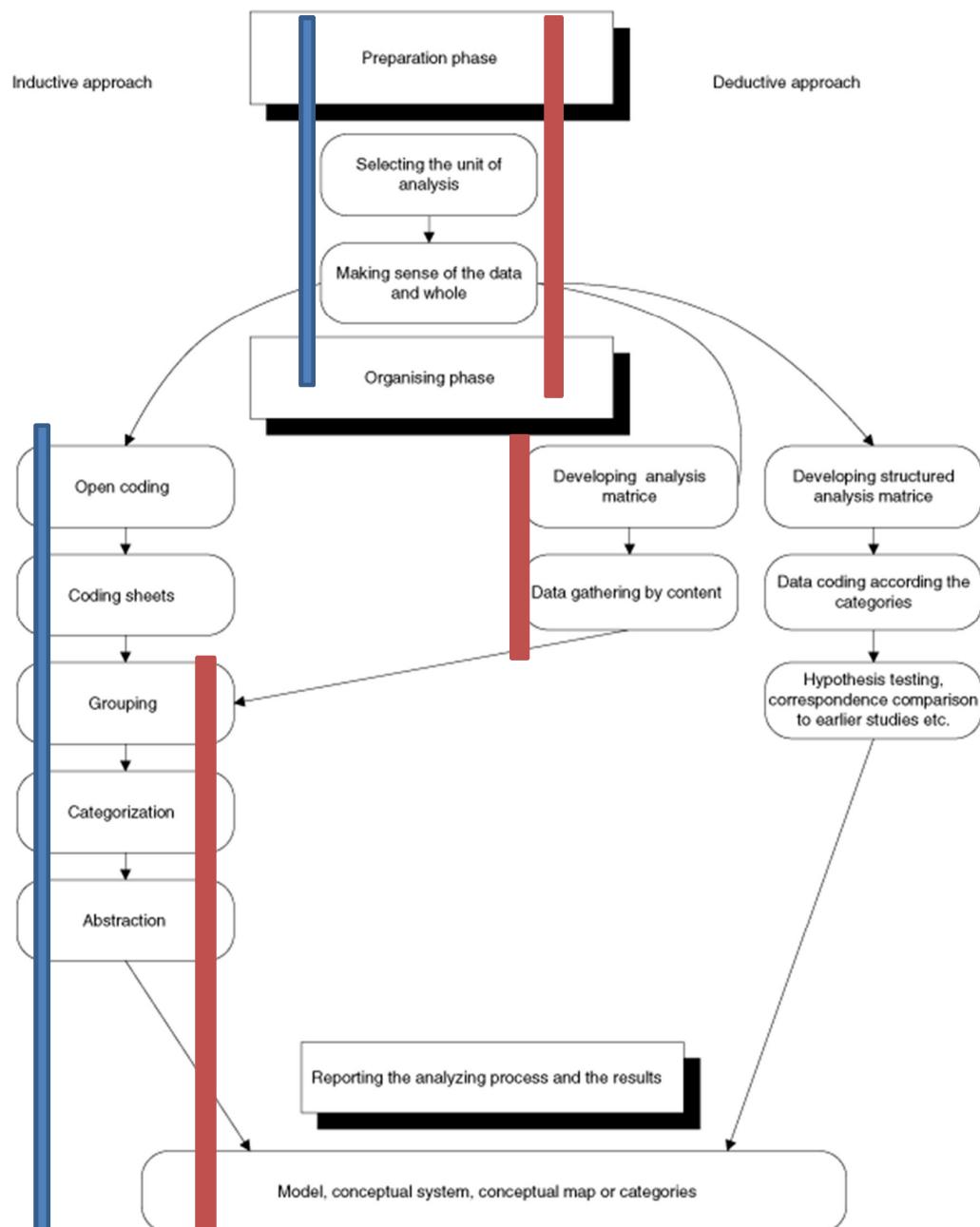


Figure 10. Preparation, organizing and reporting phases in content analysis (Elo and Kyngäs, 2008, p. 110)

The three main phases (preparation, organizing and reporting the analysing process and the results) are both deductive and inductive analysis (see Figure 10). Systematic rules for data analysis do not exist, the main issue in content analysis is that a piece of text with many words is classified into categories (Weber, 1990).

This thesis has been done with qualitative content analysis, using the inductive approach in publications I and IV (marked blue), and in publications II and III both the deductive and inductive approach were used (marked red) (see Figure 10). In publications I and IV the inductive approach was used to get a data-based view to the phenomenon. In publications II and III the deductive approach was used to create and test the SHELO model, an analysis matrix was created and the data was gathered by content, after which the inductive approach was used.

#### *Model building*

Design science model building is used to construct a solution for a research problem. The model building is based on a real-world problem (van Aken and Romme, 2009). Analytical modelling uses deductive logic in describing constructs or processes (Demski, 2007). The main advantage in using models in research is transparency. Models have been used in management research, e.g. models can support the decision-making process of managers in a company (Gorry and Morton, 1989; Mun, 2008).

In this thesis model building was used in publications II and III to create and test the SHELO model in order to classify and solve information management problems and benefits in industrial maintenance. The SHELO model can be described as a reliability engineering tool.

#### *Literature review*

The literature review demonstrates the writer's knowledge of the literature about the topics relevant to the research. A literature review is more than just a summary of the relevant literature. It includes the writer's own critical and analytical evaluation of topics relevant to the research. The literature review should focus more in research published in highly ranked academic journals than in research published on conference and books. The literature review can help to define the topic and the research questions. (Myers, 2013)

The use of existing literature is important in qualitative research. In the different phases of research, like planning, analysing data, and documenting the findings, it is important to know the existing literature concerning other research, theories and methods (Flick, 2014). The literature review:

- shares the results of other studies that are closely related to the study,
- relates the study to the ongoing dialogue about the topics in literature filling gaps and extending studies, and
- enables comparing the results of previous studies with the findings of one's own study. (Creswell, 2009)

### 3.4 Data collection and analysis

#### *Publications I and II*

The empirical data in publications I and II consisted of two surveys made for experts of maintenance. The first survey was carried out with 16 maintenance professionals completing their degrees at Jyväskylä University of Applied Sciences (JAMK). In this group, 10 people represented customers and 6 suppliers of maintenance. Completing the survey was required in order to pass one of the respondents' courses, so a response rate of 100% was achieved. The second survey was done in project MAISEMA and it was sent to 327 members from 241 member companies of the Finnish Maintenance Society. 66 members completed the survey, and the response rate was 20 %. The survey questions were originally designed to collect empirical data for the first publication but it was also used in publication II because the data was "rich" and it could be analysed from a different perspective than in the first publication. The survey questions were mainly open-ended questions and they are enclosed in Appendix A. Both surveys were conducted in Finnish, the coding was done with the data in Finnish, and the main results were translated into English.

The data analysis for publication I was based on the causes of uncertainty (Zimmermann, 2000). The six categories of uncertainty were lack of information, abundance of information, conflicting evidence, ambiguity, measurement, and belief. Coding and analysis was done with NVivo software. The material from the survey was encoded first with the theory-oriented approach by using Zimmermann's classifications of uncertainty, but it was soon discovered that six categories were not enough. New content-driven six classifications were added: communication, attitude, limited vision of the whole, course of action, databases, and missing knowledge. These new classifications are presented in table 5 in Chapter 4.

The data analysis for publication II was based on the SHELO model presented in Chapter 2.4. Elements of the SHELO model were used in coding the data collected from surveys 1 and 2. In the coding, the SHELO model matrix was used so that it was possible to use only one element or two elements in the coding. For example, when something was

related to organization, element O was the choice, if the same thing was also related to instructions, the choice was element S. This made the whole coding S-O. If there were more than two connections, coding was used only to two elements at the time, but the same thing could be in more than one coding. For example, when something was related to people interactions, maintenance plans and materials needed, there were codes L-S, S-H, and L-H. The coding and analysis were done with software NVivo.

### *Publications III and IV*

The empirical data for publications III and IV was collected from interviews with Finnish companies in project DIMECC S4Fleet. The interview data was collected from four different departments of an original equipment manufacturer, and from three customer companies who use the product, see Figure 11. Company D is a global conglomerate serving many industries with products and service. From division 1 (D1), the interviewees were a manager and an expert who both had a long work experience. These interviews lasted two hours. In D2 there was only one interview where there were two interviewees, both service specialists. From D3, a service director and a service manager were interviewed at the same time. The interview lasted two hours. From division D4, a service manager and a service tool specialist were interviewed together in a two-hour session. Customer 1 is a global forest industry company, and people from a pulp mill were interviewed. From company C1, a maintenance development manager, an automation engineer and a maintenance manager were interviewed together. The duration of the interview was a little over two hours. Customer C2 is a global company working with technologies and complete lifecycle solutions for marine and energy markets. In company C2 there were two interviews, and a general director and a digitalization director participated in them. The duration of both these interviews was about two hours. Customer C3 is an electricity distributor and has district heating services. In company C3, an operation manager and a protection specialist were interviewed, and both interviews lasted about two hours. All interviews were theme interviews with semi-structured questions, presented in Appendix B.

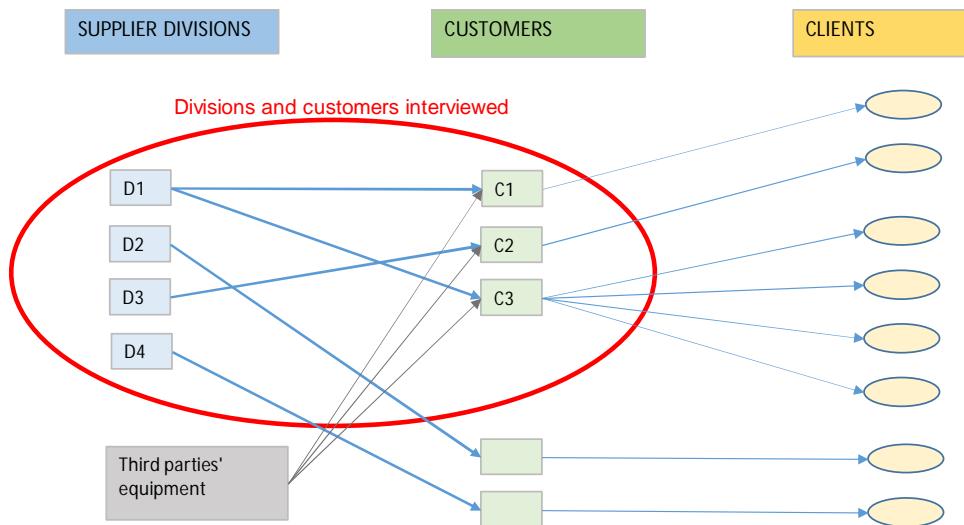


Figure 11. Interviewed persons in fleet divisions and customer companies.

The interviews were originally conducted to identify and develop the offering of products and services. The secondary data answers were interesting, so the authors decided to analyse the answers with the SHELO model for publication III and analyse the data more from the perspective of data sharing for publication IV. All interviews were conducted in Finnish, the coding was done with data in Finnish, and the main results were translated into English. Publication III was done to test the SHELO model with different data. In project DIMECC S4Fleet, open data and data sharing were important aspects, and thus these and thus these issues were important in the analysis. For both publications, the coding and analysis were done with NVivo.

#### *Publication V*

As opposed to the other publications, publication V is a literature review. The purpose of the publication was to search for articles about eMaintenance systemically. The literature review presented in this publication was carried out by utilizing a number of academic databases, including Scopus, SpringerLink, ScienceDirect, and Google Search. These databases were selected due to the high number of academic and peer-reviewed journal articles available concerning eMaintenance. The search terms used were eMaintenance, e-Maintenance, E-Maintenance and EMaintenance. 170 papers were selected for further checking, of which 48 papers were analysed.

## 4 Research contribution

### 4.1 Summary of the publications

The results of each publication are summarized in this chapter. In chapter 4.2 the main results of the whole thesis are summarized from the point of view of the research questions.

#### *Publication I*

The main objective of publication I was to recognize problems in information management in maintenance, as well as to learn about critical information breakdowns. The literature review revealed that information gaps in maintenance have not been studied much. However, problems have been presented partly when trying to improve maintenance actions, e.g. eMaintenance, different concepts in developing maintenance, and so on. Problems in practice were explained by analysing two surveys directed to maintenance professionals.

Poor maintenance is one of the major causes of problems in production (Shyjith et al., 2008). The technical competence of the personnel influences the production and maintenance costs (Al-Najjar, 2007). Lack of equipment and lack of knowledge are both common in maintenance management organizations (Crespo Márques and Sánchez Herguedas, 2004). In reducing downtime, improving the quality of production and increasing productivity, maintenance software systems play an important role (Shyjith et al., 2008). Different data sources are used in maintenance to give support to the decision process. There is great potential to use advanced maintenance technologies to improve the knowledge, experience and competence of the personnel with training (Al-Najjar, 2007, Al-Najjar and Alsouf, 2003).

Turning outsourcing and business strategies into service-oriented ones affects the maintenance actions. The relationships between the service provider and the customer will become closer than before. E.g. in aircrafts the technical systems in maintenance are complex and the amount of information is expanding. New technology and innovations create new needs for maintenance. The producers and suppliers of maintenance products, like software and hardware products, and customer services are facing challenges of keeping up high quality and increasing the service levels for complex technical systems with multiple products, suppliers and customers (Gómez et al. 2009; Candell et al., 2009).

The analyses of the surveys were partly based on Zimmermann's framework (2000). The new data-driven classifications are presented in table 5. According to the surveys, the main problems in maintenance are lack of information, conflicting evidence, communication, attitude, limited vision of the whole, course of action, and missing knowledge. Lack of information can be linked typically with poor documentation, e.g. needed information is missing or the details are incorrect. However, lack of information can usually be solved by asking somebody who knows, but this takes time. Conflicting evidence is also usually linked to documentation, but this can be very difficult to solve - which values are right if several different values exist, e.g. wrong spare parts have been purchased. Conflicting evidence is a very problematic issue in maintenance. Especially in outsourced maintenance it is important that the service provider gets enough information from the customer. Communication is in an important role to get everything done right and on time. Communication is a difficult issue, and misunderstandings can occur easily. Attitude problems are difficult to detect, but a bad attitude can create problems both in communication and in maintenance actions. The next two problems are organizational and management problems. A limited vision of the whole and the course of action can be improved by training and updating processes. The last main problem is missing knowledge, and this can be difficult to solve. The organization may be fragmented and the knowledge needed is not always available. Table 6 summarizes the main problems and solutions to solve them.

Table 5. New data-driven classifications of problems in maintenance information management.

Cause	Description	Impact
Communication	The customer thinks that the supplier knows everything. The supplier wonders why the customer does not share information.	Better processes for sharing information are needed.
Attitude	That pump is not working properly. This is not my task. Somebody should fix it.	Transfer to certainty cannot be achieved by gathering more data, but rather by transforming available data to appropriate information.
Limited vision of the whole	The maintenance staff think only of their tasks and the production staff think only of their own processes, and nobody is concerned of the whole.	
Course of action	New processes may have been created but nobody uses them because “ <i>we have always done it this way</i> ”.	Training for processes is needed.
Databases	Maintenance data is saved in different kinds of databases.	Access to databases must be organized.
Missing knowledge	The needed skills are not available.	Help from a skilled person is needed.

Table 6. Classifications of problems and solutions to reducing their occurrence (Metso, 2013)

Classifications	Solution to reducing the occurrence
Lack of information	The situation is improved by gathering more relevant information from different sources.
Conflicting evidence	An increase of information does not reduce uncertainty. Checking and deleting wrong information might help to transform the situation to certainty. High quality data / relevant data
Communication	Communication problems between people are common. Fortunately, meetings are easy to organize.
Attitude	This is a difficult issue to solve, especially when maintenance has been outsourced. Training is needed.
Limited vision of the whole	This is close to the previous and next classifications. More training may be needed.
Course of action, which means that the workers can have different ways to do something as opposed to how it is supposed to do according e.g. the quality manual	This is quite closely related to attitude and a limited vision of the whole.
Missing knowledge	The needed skills must be acquired.

These classifications can be only partly considered as outsourcing problems. Old methods of doing things are used in the organization, and even new processes have been developed. Training is needed. Communication is one of the key components to improve the whole maintenance actions.

#### *Publication II*

The purpose of publication II was to identify and categorize problems in the knowledge management of industrial maintenance, and to support successful maintenance through adapting the SHELO model. The collected data was maintenance related, for example maintenance action, information management in maintenance, etc. Data did not included

aspects of risk management, safety or security. Therefore, those were excluded in this research paper but those can be investigated with SHELO model if data contain those aspects.

A complex organizational structure can cause problems in maintenance actions (Swanson, 2003). Also tendencies towards service-oriented production increase complexity (Pawar et al., 2009). In maintenance functions, the different levels of skills in the personnel, organizational and managerial complexities, as well as technical aspects have to be taken into account (Organ et al., 1997; Shafiei-Monfared and Jenab, 2012). Increasing information flows puts pressure on the information processes to support the decision making in companies (Swanson, 2003; Crespo Marquez and Gupta, 2006; Shafiei-Monfared and Jenab, 2012). There are many software products in industrial maintenance, and information sharing and communicating between different parties is difficult (Candell et al., 2009). The main problems in maintenance (Pipek and Wulf, 2003; Al-Najjar, 2007; Metso, 2013) are lack of information, communication problems, and the fact that instructions are not available.

Integrating maintenance systems to an organisation's IT systems streamlines the decision making process (Swanson, 2003; Crespo Marquez and Gupta, 2006). Triantaphyllou et al. (1997) recognised that support to decision making will lead to better understanding of problems, and more successful solutions can be found. Successful maintenance requires paying attention to humans, technical systems and organizational settings (Thenent et al., 2013). The literature review on successful maintenance highlighted the following points: technical knowledge alone is not enough, positive social factors such as clear communication are needed, and technical, commercial, organizational and legal arrangements are needed (Thenent et al. 2013; Simões et al. 2011).

The SHELO model was modified from the SHEL model to be used in industrial maintenance, and it comprises five elements that interact with humans, Liveware (L): Software (S), Hardware (H), Environment (E), and Organisation (O) (Metso et al., 2016). New data-based services can be created when data-sharing benefits are identified and classified for example with the SHELO model. In this thesis, the SHELO model has been used both to find out problems in maintenance and to develop maintenance information management in order to execute successful maintenance. Table 7 shows further examples of relevant factors in industrial maintenance and how they are categorised in the SHELO model.

Table 7. The contents of elements in industrial maintenance

Content in industrial maintenance	
S Software	Maintenance procedures Installation instructions Plans and schedules (Automated) algorithms of condition monitoring Regulation (regarding e.g. pressure vessels, nuclear power plantsetc.) Warranty clauses
H Hardware	Tools Materials Objects Equipment Computers Buildings / Physical infrastructure
E Environment	Environmental context Temperature, Noise Economic environment
L Liveware	Humans (operators, maintenance technicians, managers, designers, etc.) People interaction (L-L) Personal attitude Skills and education Availability of personnel

The SHELO model is a useful framework to analysing industrial maintenance systematically. It can be used to categorize problems and benefits as well as to identify appropriate solutions to problems. Problems in information management can be identified by analysing survey data with the categories of the SHELO model. The main findings in the study were:

- unavailability of information due to interactions between humans and procedures and IT systems
- communication and attitudes in information sharing (interaction between humans)
- communication between organizations and departments
- software, including procedures and IT systems that provide incomplete or flawed information

Technical systems and instructions are not enough to execute successful maintenance, there is always a need for communication and the “human touch”. Not having proper communication with people can sometimes lead to misunderstandings about instructions or supposing that somebody else is responsible for the tasks. On the other hand, technical

systems are needed in order to organize the data sharing. The SHELO model can be used also to develop solutions for identifying weaknesses and strengths in industrial maintenance. Problems in information sharing can be reduced by improving communication with the service providers and using CMMS systems.

### *Publication III*

The purpose of publication III was to use the SHELO model to understand the most critical data and information management problems and opportunities in the fleet environment. Fleet data is scattered to different organizations and departments, and inter-organizational data sharing is not widely adopted. Companies have a view only to the fleet of assets they own. The equipment provider does not have access to all data of the fleet of assets that they have produced, even if the provider has knowledge of their products to use the equipment e.g. fuel-efficiently or to avoid harmful misuse of the equipment. Data is not shared between companies, but there are difficulties also in transferring data inside a single company. The SHELO model was used to identify and solve the challenges related to data sharing.

The main benefits and potential identified with the SHELO model were:

- technology available,
- support to decision making,
- transparency enables new business,
- IoT will help in data sharing,
- data sharing potential is known,
- better services can be created by combining data from different systems,
- big data makes it possible to manage the customer's equipment in fleet,
- it is possible to discuss matters with clients at many levels,
- clients want support for decision making and data analysis,
- eco-friendly solutions can be developed, and
- new business models can be created.

The main barriers to sharing data are:

- ownership of data,
- data quality,
- technical problems in data collection,
- defining which data is difficult to monitor,
- data architecture,
- amount of big data,
- data facilitator missing,
- lack of knowledge,
- win-win not understood,
- limitation of IT systems,
- rules are not clear,
- co-operation with others is difficult,
- big data is shared only case by case,
- regulations and laws are unclear/local,
- suspicion that someone will understand the data better and fear of misuse of data,
- it is difficult to contact the “right person”,
- clients are not willing to pay for monthly service, and
- missing standards.

The SHELO model could be used to analyse the barriers and benefits in data and information management. The identified barriers and benefits could be categorized for further analysis to classified problem areas and for identifying solutions. The main problem was the ownership of data. Companies do not recognize a win-win situation in data sharing. Data sharing can lead to stronger business advantages in the maintenance ecosystem. The barriers are quite well known in companies, but the benefits have not become familiar in the field of maintenance.

#### *Publication IV*

The purpose of publication IV was to address the barriers and benefits for data sharing within asset management by suggesting an ecosystem solution. Big data and IoT can increase the amount of data on asset management. Data sharing with an increased number of partners in the area of asset management is important when developing business opportunities and a new ecosystem.

Data sharing was done first in the Open Data concept in which governmental data was shared to anyone without copyright restrictions (Murray-Rust, 2008). However, in organizations not all data can be available for everybody. In the maintenance ecosystem the organization defines the internal and external communications relevant with respect to the assets, asset management and asset management system: what, when, to whom, and how to communicate (ISO 55002, 2014) (see figure 12). The organization has to consider the risks, roles and responsibilities, as well as the processes, procedures and activities in asset management, information exchange, and the quality and availability of information in the decision-making processes (ISO 55001, 2014).

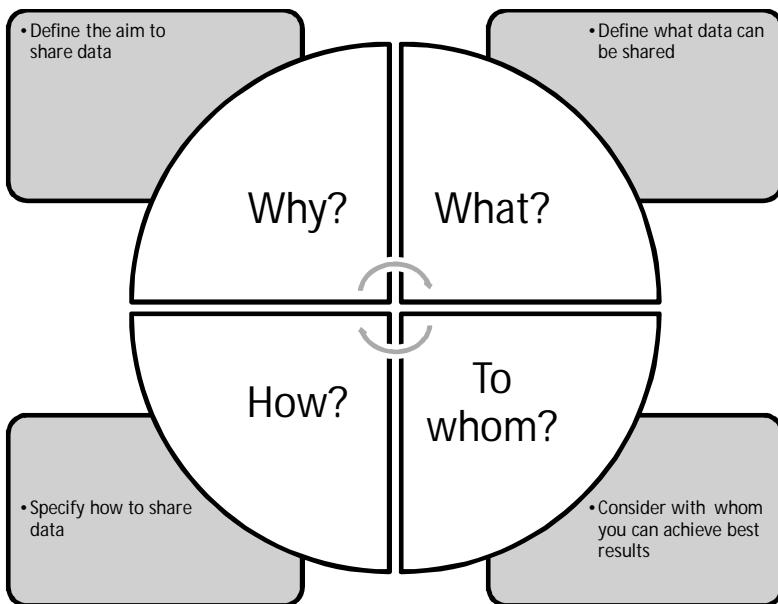


Figure 12. Data sharing in ecosystem (based on ISO55002, 2014)

In publication IV, understanding of the barriers and opportunities for data sharing was constructed by using both theory-based data and data based on interviews. The barriers and opportunities were classified according to the classifications created by Janssen et al. (2012), presented in chapter 2.2 in tables 1 and 2.

#### Barriers in data sharing

Of the *institutional level barriers*, the main barrier is the ownership of data. The customer owns the data and wishes to own the data also in the future. Confidential data is not allowed to be shared, and also data connected closely to the business is not wanted to be shared. The maintenance ecosystem is fragmented and there are hundreds of doers who have their own computer systems which do not work together. It is difficult to define one common platform for sharing data. Maintenance services have been sold traditionally by

man-hours, and it is challenging to sell data-based services in maintenance because the customers are used to getting staff at the same time.

Another barrier is *the complexity in handling data*. The increasing amount of collected data causes more complexity in handling the data. Data can be collected from different databases, and also defining monitoring data can be a challenge. Process data is not collected with equipment, but health data can be collected with equipment with an intelligent sensor. The link between maintenance databases and automation systems may be missing. Sometimes it is not clear which data can be collected by a sensor and which data must be entered manually. The quality of the data is not high enough.

Lack of knowledge and lack of comprehension are the main reasons for *barriers for the use of open data and participation in the open-data process*. Data is not shared because some doers believe that someone else will understand the data better. The win-win situation is not understood. Online data is not available, even though it would offer other information for those who need it. The same concerns big data. Data is shared and combined only case by case but not in a planned way, and also data from different sources is not used properly.

*Legislation barriers, information quality barriers, and technical level barriers* also exist. Information quality problems are typically of the type that the data in the IT system is not accurate enough or people have made mistakes in inputting the data to the system. The technology is available to collect and combine big data, but standards are missing.

#### Benefits of information sharing

*Political and social benefits* can be included in the “sharing ecosystem”, which affects companies and service networks positively. Data sharing enables new business models and new ecosystems. *Economic benefits* can be achieved by developing the value of services based on data sharing. The equipment could create data for the maintenance staff automatically, e.g. work orders. This is one example how automation in data handling can give *operational and technical benefits*. As well as big data collection, sharing and analysis can support e.g. optimizing energy consumption. Remote support, fault diagnosis, and health monitoring can create new business models by the use of intelligent equipment and sensors.

The *potentials for data sharing* are increasing because IoT makes online data possible to be used in maintenance actions. If data user rights and sharing methods can be agreed on, data sharing has good potential to create new services to the maintenance ecosystem.

In companies the barriers to share data are usually well known, but the benefits are not recognized. The traditional way to understand value creation is in the form of a stream, or a chain, where the actors e.g. input raw material for getting outputs, finished products. Maybe companies are not familiar with data-based business in industrial maintenance. In this publication we presented the AaaS model (described in chapter 2.1), in which

information flows are smooth and well-defined to all actors, and some problems and barriers can be avoided by using the model.

#### *Publication V*

Publication V is a review of the existing academic literature, and it describes the key components of eMaintenance. eMaintenance has been described as a tool for integrating companies' production and maintenance operations with ICT solutions (Crespo-Marquez and Gupta, 2006; Garg and Desmukh, 2006; Jardine et al., 2006; Levrat et al., 2008; Muller et al. 2008A). eMaintenance was selected to a systematical literature review because eMaintenance can be seen as a solution to some issues in information and data sharing in maintenance.

eMaintenance is a technology connected to other systems to assist in data collecting, analysing and defining maintenance tasks, which makes it possible to share "right data to the right person at the right time". eMaintenance uses various data sources and utilizes different tools and techniques. The term "Intelligent Maintenance Centre" is used because eMaintenance collects data and provides relevant data to be used in the development of maintenance tasks. Data is shared smoothly, and experts are used to give support in maintenance functions (Baglee and Knowles, 2012; Iung and Crespo-Marquez, 2006)

The main elements of eMaintenance are base knowledge, data acquisition system, models, and performance reporting. Base knowledge can be seen as understanding of the physical systems to be maintained, critical features and characteristics from which performance and health can be predicted. The data acquisition system is an ICT system for data collecting.. Models support the decision-making process in maintenance. The performance reporting system reports of production and other services. ICT is integrated to a network of machines, and eMaintenance gives potential to share data effectively. (Duffuaa and Raouf, 2015)

The literature review found research gaps in the definitions and managerial implications of eMaintenance. eMaintenance is defined in several different ways, and it is difficult to understand what is meant with the different definitions. eMaintenance is presented as a concept in literature but not as an implemented system. It is interdisciplinary, connecting maintenance, ICT, data sciences, and management knowhow together in the decision making process.

## 4.2 Summary of the results

The objective of this thesis was to identify and categorize information management problems and benefits in maintenance and to develop solutions to improve maintenance information management.

Table 8 summarizes the main points of the five publications in this thesis.

There were two research questions in the thesis. The first research question was: *How to identify, model and manage problems and benefits of information-based maintenance?* Publications I, II, III, and IV responded to this research question. The basis for the research in publication I was to find whether any problems existed. Is it worth studying information management in industrial maintenance? According to the survey results there were problems, and it is necessary to study this area more. In publication I Zimmerman's (2000) framework of uncertainty was used. In publication II, III and IV the SHELO model was used in categorizing and classification. The SHELO model was a very good tool to classify both survey and interviews results. A framework or model is needed when categorizing and classifying things systematically.

In publications I to IV, the following problems in information management in maintenance were recognised:

- problems in communication,
- attitude,
- lack of information,
- information quality, and
- complexity of data handling.

Also the main benefits were recognized in publications I to IV:

- the technology is mainly available,
- positive social factors like clear communication is needed,
- data sharing can create new business, and
- data sharing improves maintenance actions.

Table 8. Summary of the publications in the thesis.

	<i>Publication I</i>	<i>Publication II</i>	<i>Publication III</i>	<i>Publication IV</i>	<i>Publication V</i>
<b>Title</b>	Information gaps and lack of competence in maintenance	Adapting the SHEL model in investigating industrial maintenance	Identifying fleet data sharing needs, problems and benefits with the SHELO model	An ecosystem perspective on asset management information	Maintenance as a combination of intelligent IT systems and strategies: – a literature review
<b>Objective</b>	Recognizing problems in information management in maintenance, as well as to learn about critical information breakdowns.	Identifying and categorizing problems in knowledge management of industrial maintenance, and adapting the SHELO model to support successful maintenance.	Using the SHELO model for identifying the most critical data and information management problems and opportunities in the maintenance environment.	Addressing the barriers and benefits for data sharing within asset management by suggesting an ecosystem solution.	Providing a review of the existing academic literature and describing the key components of eMaintenance.
<b>Research question</b>	1	1,2	1,2	1,2	2
<b>Research method</b>	Content analysis	Content analysis Model building	Content analysis Model building	Content analysis Model building	Literature review
<b>Empirical data</b>	Surveys	Surveys	Interviews	Interviews	Literature sample of articles
<b>Main results</b>	The main problems were categorized with qualitative analysis: Lack of information, conflicting evidence, communication, attitude, limited vision of the whole, course of action, and missing knowledge.	The SHELO model is a useful framework for analysing industrial maintenance systematically. The main findings were: unavailability of information, communication and attitudes in information sharing.	The main benefits and potential identified with the SHELO model were: technology is available, transparency enables new business, IoT helps data sharing. The main barriers to share data: data ownership, win-win not understood.	Potential for data sharing is increasing because IoT makes online data possible to use in maintenance actions, a sharing ecosystem. The main barriers are: confidential data, old traditions, data quality, attitude.	The key components in eMaintenance are advanced use of ICT, integration of different data sources, expert centres and support to decision makers. Cooperative maintenance is challenging.

The second research question of the thesis was: *How can industrial maintenance be improved by information management?* Publications II, III, IV and V responded to this research question. Publication V was a literature review about eMaintenance, and it showed that modern software systems and intelligent sensors are needed in successful management in maintenance. Efficient communication is a prerequisite of successful maintenance management. Transparency in information sharing improves both successful maintenance actions and helps create new services in maintenance. The main difficulty in data sharing is to start data sharing with the right parties. Not all data can be shared, but companies define why to share data, what relevant data can be shared, to whom data can be shared, and the easiest part is how data is shared (see figure 12 in chapter 4.1). When the maintenance network is stable, it is the right time to define the steps presented above to get the maintenance services improved. Data sharing is the first step in the “sharing ecosystem”, in which companies can get advantage and improve the whole maintenance functions. Also attitude and the culture to share information in companies affect maintenance a lot. If the win-win situation in sharing information is not fully understood in companies, there will be difficulties in maintenance management. Modern ICT makes it possible to share data between parties who need the data.

## 5 Conclusions

This chapter summarizes the main findings of the thesis. Theoretical contributions are presented first, then five practical implications are defined through the results of the study. Evaluation of the research is done with guidelines presented for interpretivist research. Finally, recommendations for further research are presented.

The main challenges and advantages in maintenance, together with solution propositions are presented in Figure 13. There are various methods to minimize the occurrence of missing data. Information gaps can be reduced by regarding the potential problems of data transmission. Human actions affect successful maintenance, for example communication and interactions with other people. The challenges are mostly related to the availability of data and lack of communication. In this thesis, the strengths and weaknesses in maintenance information management were identified and classified based on the framework of Zimmermann (2000) and the SHELO model. The systematic way to do the identification of strengths and weaknesses was useful and made it possible to improve the maintenance actions based on the analysis. The new ecosystem which allows sharing relevant data smoothly can be the key to successful maintenance, in which also win-win is recognised.

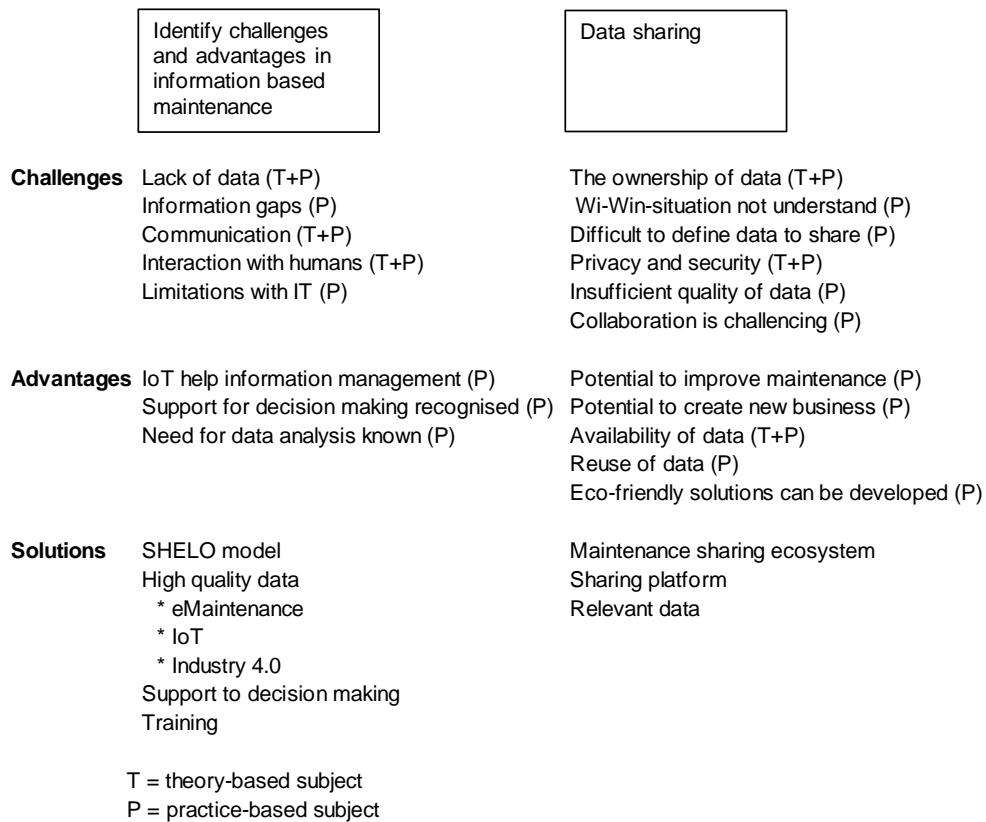


Figure 13. Main challenges, advantages and solution propositions in the information-based industrial maintenance ecosystem.

The main challenges and advantages were presented in Summary of publications (Chapter 4.1). Propositions for solutions are presented in the next two chapters: Theoretical contribution (Chapter 5.1) and Practical implications (Chapter 5.2).

## 5.1 Theoretical contribution

### *Data sharing*

The organization specifies the key point of how to communicate with employees, suppliers and contracted service providers, why data is shared, what data, to whom, and

how data is shared (ISO 55000, 2014). In the Open Data concept data sharing was allowed the first time with governmental data to anyone without copyright restrictions (Murray-Rust, 2008). Also in science and technology research, data sharing has proved as a good practice, it enables data-based new questions for the researcher and advances research and innovations (Wallis et al., 2013; Kim and Stanton, 2012). The basic hypothesis of data sharing is that it can generate new value, but data is context- and time-dependent and taken out of context, open data loses meaning, relevance and usability (Dawes, 2012; Strong et al., 1997). The barriers and opportunities in data sharing have been presented by e.g. Janssen et al. (2012) and Saygo and Pardo (2013). This thesis contributes to the current research area of data sharing by showing that data sharing has good potential in developing collaboration in the maintenance ecosystem.

#### *SHELO model*

The SHEL model has been created to study the interactions between individuals, systems and the environment (Hawkins 1987). Originally the SHEL model had three elements interacting with humans (called Liveware): Software, Hardware and Environment (Edwards 1972). Person-to-person relationship was added (Hawkins and Orlady, 1993), as well as the element of organisation (Chang and Wang, 2010). The SHEL model was used to investigate aviation accidents, and then it was noticed that some accidents were related to airplane maintenance, so the model was used in aviation maintenance (Edwards, 1972; Lufthansa Technical Training, 1999; Licu et al., 2007). The SHEL model has been used in maritime organizations (Chen et al. 2013) and also in nuclear power generation (Kawano 1997). The SHELO model can be used in industrial maintenance to discover the strengths and weaknesses in information management and maintenance actions. In this research, the SHELO model was created and tested with two different data sets.

#### *Communication*

Software systems such as PLM and eMaintenance (e.g. Lee and Wang, 2008, Candell et al., 2009) can solve challenges related to information sharing and communication between different parties in industrial maintenance. However, software does not solve all problems (O'Dell et al., 1998). Technical knowledge alone is not enough in successful maintenance, also clear communication as well as technical, commercial, organizational and legal arrangements are needed (Thenent et al. 2013; Simões et al. 2011). The main problems in industrial maintenance are lack of information, communication problems and the fact that instructions are not available (Pipek and Wulf, 2003; Al-Najjar, 2007; Metso, 2013). The results of this study highlight the importance of communication.

#### *eMaintenance*

eMaintenance has been defined as a concept, a philosophy or a technology, which makes it challenging to create a unified way of understanding it (Iung et al., 2009; Lee and Ni, 2004; Crespo-Marquez and Iung, 2008; Baldwin, 2001; iSCADA; Levrat et al., 2008). However, eMaintenance can be seen as a strategy within maintenance that is supported

by the use of ICT and new technologies. It utilizes real-time data from different sources to provide support to decision makers. eMaintenance solutions need to be integrated with other systems, and it is important that the other information systems allow data transfer between different environments, and all systems in the eMaintenance network can exchange information in an efficient and usable way (Muller et al., 2008B). Condition-based maintenance (CBM) is a key component of eMaintenance, sharing features such as predicting, preventing, and performing maintenance effectively and efficiency (Duffaa and Raouf, 2015). Predictive maintenance (PdM) detects early signs of failure in order to make maintenance operations proactive, and the potential of PdM is increasing because IoT, remote maintenance and eMaintenance can support PdM (Selcuk, 2016). eMaintenance can be seen as a part of a solution to improve information management in the maintenance ecosystem.

## 5.2 Practical implications

The sharing ecosystem is a wide concept where a common platform enables data sharing.

### *New ecosystem - Sharing ecosystem*

In the future, data can be seen as a part of a “sharing ecosystem” which will work positively in companies and service networks. Transparency in data sharing will enable new business models. There is a need for a lot of dialog with different parties when creating a new ecosystem. The new models can be based on data sharing, and that is why more responsibility is needed. If “risk and revenue sharing” is the target, also the supplier needs to give more and take more risks and responsibility in order to co-operate.

### *Common platform*

Transferring into platform-based business where data sharing is of major importance would be a fundamental change for many industrial companies operating with traditional business models. Most companies have been cautious in adopting practices that would take them towards a common, inter-organizational platform. However, the real value of fleet management lies in integrating and analysing data of various assets, although comparing assets of different ages is not always straightforward.

### *Data sharing*

At the moment, data is shared and combined in companies only case by case when needed. The ownership of data is important to companies. Companies own the data, they want to own it in the future as well, and are not willing to share if benefits are not clear. Complexity is growing and it is difficult to notice important data automatically in the very large amount of collected data. This opens the opportunity to offer analysis services to companies. In future there may be more service providers in data management than there is now. Rules to sharing and combining data are missing, even though the advantages of

data sharing can be seen. This study has demonstrated that sharing data can promote win-win situations in the maintenance ecosystem.

#### *SHELO model*

The SHELO model is based on the SHEL model, which has been used mainly in aviation. The SHEL model has elements to study human interaction. In the SHELO model, also elements to study organizational issues are implemented. The SHELO model has proved to be a tool to classify both weaknesses and strengths in information management in industrial maintenance. A systematic method to classify is needed in order to make an extensive analysis, and the SHELO model suits this well.

#### *eMaintenance*

eMaintenance is a system where machines are networked, data is collected, shared and analysed, and experts are used to support decision making in maintenance. Remote maintenance operations and decision making make it possible to log in anywhere and with any devices, manpower on the customer's site can be reduced, the use of expertise is easy, and new features can be added. The business process can be integrated and cooperative/collaborative work can be done in maintenance, and it is easy to design and synchronize maintenance with production, maximizing process throughput with eMaintenance system. Fast online maintenance, real-time remote monitoring, alerts, high rate communication to experts, and a maintenance support system can be organized within eMaintenance. Support to predictive maintenance, prognostics and health management systems can be implemented in the eMaintenance system. IoT enables the smart use of intelligent sensors etc. in eMaintenance systems. eMaintenance, IoT and Industry 4.0 can be the foundation to receive high quality maintenance data.

### **5.3 Evaluation of the research**

Evaluation of a research can be done by multiple different frameworks. The evaluation framework is chosen to follow the selected methodology and methods. In this thesis the theoretical paradigm is interpretivist, as described in chapter 3.2

Credibility, transferability, dependability and conformability are used in the evaluation of qualitative research. In the evaluation of the quality of qualitative research *credibility* means almost same as internal validity, *transferability* corresponds with external validity, *dependability* with reliability, and *conformability* with objectivity. These categories are discussed below. (Wahyuni, 2012)

*Credibility* discusses the accuracy of data, and it concerns whether the study measures or tests what was planned (Wahyuni, 2012). It is almost the same as validity. Validity defines what the research really measures compared to what it was meant to measure or how

truthful the research results are (Joppe, 2000). The data collected with surveys for publications I-II was from maintenance experts. The data for publications III- IV was from interviews of maintenance managers and directors. The collected data was relevant, and all analysis was based on that data. The articles handled topics as was planned, and there was enough data. Analysis triangulation was achieved with different analysis of same kind of results in publications I and II, and the idea was the same with publications III and IV. Publication V was a literature review, and extensive search in existing literature was carried out.

*Transferability* indicates the level of applicability to different settings or situations in research execution. If the data from a qualitative study is not reproducible, it may be possible to use the data in different settings. With careful adjustments in settings, research findings can be transferred into a different study (Wahyuni, 2012). The findings were based on a wide survey and interview material, and the observed practices can possibly be transferred to other industries. Of course, different industries have different problems and solutions, but issues with information management are common in other industries as well. Paying attention to improving information management can improve actions also in other industries.

*Dependability* considers how all changes in the settings affect the research execution. Dependability can be realized by a precise explanation of the research design to enable other researchers to follow a uniform research framework. This means almost same as reliability. By definition, reliability means that the results of the study can be reproduced with similar methodology (Joppe, 2000). Also the research process must be documented with enough details included (Wahyuni, 2012). In this thesis all steps in the research were documented in the thesis or the publications included in the thesis. The research design can be followed by other researchers.

*Conformability* ensures that the findings are results of observation rather than the researcher's own opinion. Documentation of the data and the research progress makes it possible to revise both the research process and research outputs by tracing the objectivity of the research step by step (Wahyuni, 2012). In this thesis, objectivity was taken care of by taking to the analysis only data collected from the participants, not from the researcher's own preferences. Documentation of the data and the progress of the research was done meticulously, and it is possible to trace the research step by step.

## 5.4 Future research

*Firstly*, the increasing amount of data and information highlights the importance of information management in maintenance. Intelligent equipment and IoT make data collection easy, but the issue is how to use the data and with whom to share it. There are many players involved in maintenance. For example, more research is needed to widen the investigation to find out clients and third-party equipment suppliers' needs in sharing data. Data sharing has a positive influence on maintenance costs and quality, but so far research has not focused on the win-win situation in sharing data in maintenance environment.

*Secondly*, the concept “sharing ecosystem” needs research. In practice it means that companies share risks and revenues, but how to do it is the problem. In order to start a “sharing ecosystem”, companies must first start to share the information needed. In academic research data sharing is done with the Open Data view, public data is shared to achieve transparency and public benefits. Academic research about the “sharing ecosystem” in maintenance information management has not so far been done properly.

*Thirdly*, research about joint platforms in information management in the maintenance ecosystem is missing. A new research area would be to coordinate subcontractors and clients to create a new solution or a pilot to define new rules and a platform to share data. Standardized ways of action in information sharing are needed in the maintenance ecosystem.

*Finally*, research is needed to investigate the root causes to solve the problems found in this research and to create new methods to develop collaboration and data sharing rules in the maintenance ecosystem. Industry 4.0 and Maintenance 4.0 may offer some solutions to these problems in the future. However, Industry 4.0 and Maintenance 4.0 need to be investigated in the future as well.



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## **Appendix A: Open-ended questions in surveys 1 and 2**

**Background information:** Name, position, work history

Have you been in a situation where some data, information or knowledge has been missing in maintenance?

How did you get this missing data or information?

How did you solve the problem of getting the missing knowledge?

How did you handle the situation?

Was the maintenance schedule delayed? Were extra costs caused in maintenance?



## **Appendix B: Interview frame**

**Background information:** Name, position, work history

### **Development of services**

- 1) What service do you offer to your customers?
- 2) How is service developed in your department?
  - a. Are there any problems or challenges in service development?
- 3) What processes do you have in service development?
- 4) An example of service: how did you begin to develop service, what problems exist, what kind of approach was used in service management?
- 5) What kind of information-based value do you offer?

### **Data management**

- 6) Current data collection: what and where?
  - a. What challenges are there in data collection?
  - b. Does the customer give data and information?
- 7) Who owns the data of equipment or process? Who has access to the data?
- 8) What data is shared between different parties? Which data would be beneficial?
- 9) How to add to the value of data?
- 10) How extensively is the collected data analysed?
  - a. Is there unused potential?
  - b. Is the data analysed for own development or do you try to give added value to the customers?
- 11) Can the analysed information be used to support decision making?
  - a. How is data for decision making used?
  - b. Is there any analytics to improve decision making?
- 12) What functions and decision making can be improved with better data and/or analytics?
- 13) Data management: systematic processes or case-by-case ones?

### **Data modelling**

- 14) Do you use data models or standards?
- 15) What changes were needed when moving to data-based business?
- 16) How is data and/or information combined from different sources?

### **Fleet view**

- 17) What are the possibilities of an extensive amount of equipment (fleet)?

- a. What advantages could be achieved from extensive data from the fleet?  
How could the data be used?
- b. Is there any potential for save money or time? Is there potential to add offerings with added value of information?

18) Where is the most important potential to combine data?

#### **Creating a common offering** (only for divisions 1 to 4)

19) How could different departments serve customers better together?

- a. Are there customers served by different departments? Have there been any difficulties?

20) What service could different departments offer to customers together?

- a. Any advantages?

21) What new or existing customers could be served by combining resources inside the company?

- a. are there any customers to try to develop a case together?

22) A roadmap to development together with service offering?

- a. How could the departments gain advantage from collaboration?
- b. Any expectations from collaboration?
- c. How to inform the customers about the benefits?
- d. What changes are needed in the organization?
- e. How to share money?

## **Publication I**

Metso, L.  
**Information gaps and lack of competence in maintenance**

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# Information gaps and lack of competence in maintenance

Lasse Metso\*

*Faculty of Industrial Engineering and Management  
Lappeenranta University of Technology  
P.O.Box 20  
FIN-53851 Lappeenranta  
Finland*  
*\*Corresponding author: Lasse Metso  
e-mail: lasse.metso@lut.fi*

## Abstract

Information gaps or lack of competence can cause serious problems in maintenance.

This paper focuses on recognizing problems in knowledge management in maintenance, and also on learning about critical information breakdowns. The literature dealing with competence shortage in maintenance and missing data or information is discussed first. It was found that articles concerning maintenance and information gaps at the same time were few in number, meaning that more research is needed in this issue.

The method of data collection in the study is a questionnaire to maintenance professionals. According to the answers, there are several different methods to minimize the occurrence of missing information. It is more difficult to ensure that a lack of competence in maintenance will not appear, as for example a competent worker may be sick at a critical moment.

**Key words:** Lack of information, lack of competence, missing knowledge, missing data, maintenance

## 1 Introduction

Factors that influence product quality, production cost, machine condition and the length of its life are usually the quality of the input raw materials, production tools, methods and procedures, the competence of the operating and maintenance staff, and the operating conditions. The technical competence of the personnel influences the production and maintenance costs, as well as the efficiency of machine performance because this kind of competence affects the practice of operating and maintaining the machine. (Al-Najjar, 2007)

The South Indian Textile Association found that poor maintenance was one of the major causes of problems in production. Each machine needs different maintenance instructions and a trained person in maintenance work, because machine breakdown will affect the operation of the plant and increase the maintenance cost. (Shyjith et al., 2008)

The maintenance system plays an important role in reducing equipment downtime, improving quality and increasing productivity (Shyjith et al., 2008). Lack of equipment maintenance records is common in maintenance management organizations. Lack of knowledge in handling maintenance data is a common problem in identifying the causes of fault modes (Crespo Márques and Sánchez Herguedas, 2004). On the other hand, lack of competence in maintenance can lead to an increase in the equipment downtime, and a decrease of quality and productivity. The same unwanted results can be caused by lack of data or information.

The main target of this paper is to find out if there are information gaps or missing knowledge in maintenance, and if this is the case, how the occurrence can be reduced. Section 2 of this paper discusses previous literature on the topic, while section 3 focuses on methodology. The results of the research are presented in section 4, and section 5 contains conclusions.

## 2 Literature survey

### 2.1 Outsourcing and information-sharing problems

The challenge in maintenance is changing a product-oriented business strategy to a service-oriented one. The product-oriented strategy is based on transaction and exchange marketing, while the service-oriented one highlights the relation between the provider and the customer. A service-oriented business strategy requires the harmonization of support processes, such as maintenance, to the core process of the business. (Candell et al., 2009)

Outsourcing is used in maintenance increasingly. The decision to outsource is a strategic decision inside the company. Gómes et al. (2009) present a framework about management in maintenance outsourcing in a service provider company. The advantages and disadvantages of outsourcing are presented in table 1.

**Table 1. Advantages and disadvantages of outsourcing (Gómes et al., 2009; modified)**

Advantages in outsourcing	Disadvantages and risks in outsourcing
Reduction costs, at same time quality to employ a more specialized supplier	Unfilled or questionable expectations for a scenario developed to generate the process of outsourcing
Restructuring costs, changing fixed costs by variable costs in terms of the service provider	Changes in the quality for breach of agreements on services, either by the knowledge or capabilities of the supplier company, or errors in definition of the same company
Stimulates local employment through contracts with local firms	Loss of knowledge or skills through transfer to the supplier, where it is more difficult to retain and improve. This happens frequently
Obtaining a rapid budget by selling assets	Loss of control over the externalized functions, source of learning for the internal staff
Improvement of quality, for higher specialization	Dependence on the supplier could cause adverse consequences for the client (investments extraordinary)
Access to outside expert knowledge	Loss of security by staff transferred to the supplier, by hoax and illegal transmission of knowledge and information on the competence

Standardization and access to scale economies	Public and internal opinion on outsourcing jobs to another company
Flushes resources for other purposes	Loss of motivation for staff involved in the service, because it can create a feeling of alienation within the client company and result in the staff feeling that their jobs are valueless
Improves the company focus	
Improves the management of functions difficult to handle	
Optimizing routine tasks	
Sharing risk by flexibility of demand with the supplier company	
Provides legal guarantee for services	
Relationships developed between financial aspects and levels of service	
Starting point for changes in the organization	
Speed through reengineering	

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Today's providers of maintenance to industries with complex technical systems (e.g. aircrafts) are facing major challenges. A key problem is to manage the ever-increasing information flow and system complexity. There is an increasing amount of digital product information and design data provided together with hardware and software products from manufacturers, sub-system suppliers and other sources. New technology and innovation drive development and create new needs. The producers and suppliers of maintenance products and customer services are facing challenges of keeping high quality and increasing service levels for complex technical systems with multiple products, suppliers and customers. (Candell et al., 2009)

Different data sources are used in maintenance decision making processes. These data sources are for example failure data, practical experience, results of technical analysis, condition-monitoring measurements and operating data, or a combination of these data resources. The maintenance actions can be performed in the right time, preventing failure if there is relevant, accurate and good data coverage available. There is a big potential to use better maintenance technologies by improving the knowledge, experience and competence of the personnel with training (Al-Najjar, 2007, Al-Najjar and Alsyouf, 2003).

## 2.2 Uncertainty

The term "uncertainty" has a number of meanings. In preventive maintenance it is used to describe problematic issues in the time-to-failure of equipment. The major problem in preventive maintenance is to define the best time and frequency for repairing. This can affect maintenance costs and also reliability. According to Zimmerman (2000), "uncertainty" means that a person does not have enough information to make right decision in a certain situation. Uncertainties can be categorized as external and internal ones. The decision-maker can control internal uncertainties, but not external uncertainties. These uncertainties can occur because of lack of understanding or knowledge (Cavalcante and de Almeida, 2007).

Zimmermann (2000, p.192) classifies the causes of uncertainty to six categories and he states that “Uncertainty implies that in a certain situation a person does not dispose about information which quantitatively and qualitatively is appropriate to describe, prescribe or predict deterministically and numerically a system, its behaviour or other characteristic.” Details of the causes of uncertainty are presented in table 2.

**Table 2. Causes of uncertainty (Zimmermann, 2000; modified)**

Cause	Description	Impact
Lack of information	Decision maker does not have the information needed.	A situation of uncertainty can be transformed to a situation of certainty by gathering more and better information.
Abundance of information (complexity)	More data is available than a person can digest.	A transfer to certainty cannot be achieved by gathering more data, but rather by transforming the available data to appropriate information.
Conflicting evidence	There might be information available pointing to a certain direction, but some information is available pointing to another direction.	An increase of information does not reduce uncertainty. Checking and deleting wrong information might help to transform the situation to certainty.
Ambiguity	Linguistic information has entirely different meanings.	Ambiguity can be classified also as lack of information because more information helps to move towards certainty.
Measurement	An ‘imagined’ exact property cannot be measured perfectly.	This can also be considered as a lack of information.
Belief	All information available to the observer is subjective as a kind of belief and it can be considered as in a certain situation.	This situation is questionable and it can be considered as lack of information.

### 3 Methodology

The research process for this paper began with a literature review and building theoretical understanding of the different aspects of lack of data, information and knowledge in the area of maintenance.

This study is qualitative research and the data collection method is surveys. The first survey was carried out with 16 maintenance professionals completing their degrees at Jyväskylä University of Applied Sciences (JAMK). In this group, 10 persons represented customers of maintenance and 6 suppliers of maintenance. These students were “obliged” to take part in the first survey, so the response rate was 100 %. The second survey focused on the members of the Finnish Maintenance Society Promaint. The second survey was sent to 327 members, and the response rate was 20.2 %.

Table 3 shows how the survey respondents belonged to customers or suppliers of maintenance. In survey 2 there was also a group others, to which belonged e.g. entrepreneurs who were not customers or suppliers.

**Table 3. Survey respondents broken down into customers and suppliers of maintenance.**

	Respondents			
	Customer	Supplier	Other	Total
Survey 1	10	6	0	16
Survey 2	42	16	8	66

The respondents were encouraged to tell little stories about situations where there was some urgent data, information or knowledge missing. The questions were:

- Have you been in a situation where some data, information or knowledge has been missing in maintenance?
- How did you get this missing data or information?
- How did you solve the problem of getting the missing knowledge?
- How did you handle the situation?
- Was the maintenance schedule delayed? Were extra costs caused in maintenance?

The material from the survey was coded and analysed with NVivo version 10 software.

#### 4 Results

The research was started by the theory-oriented approach using Zimmermann's (2000) classification of six categories of causes of uncertainty. As soon as it was discovered that six classifications were not enough, new material-driven classifications were added. These new classifications were based totally on the material of both surveys. These classifications were not theory-based but only material-driven. More details are shown in table 4.

**Table 4. New classification and descriptions.**

Cause	Description	Impact
Communication	The customer thinks that the supplier knows everything. The supplier is wondering why the customer does not share information.	Better processes for sharing information are needed.
Attitude	That pump is not working properly. This is not my task. Somebody should fix it.	A transfer to certainty cannot be achieved by gathering more data, but rather by transforming available data to appropriate information.
Limited vision of the whole	The maintenance staff think only of their tasks and the production staff think only of their own processes, and nobody is concerned of the whole.	
Course of action	New processes may have been created. Training for processes is but nobody uses them because "we have needed. always done it this way".	

Databases	Maintenance data is saved in different kinds of databases.	Access to databases must be organized.
Missing knowledge	The needed skills are not available.	Help from a skilled person is needed.

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The coding references in both surveys are presented in table 5. This is the basis of how the research continues.

**Table 5. Coding references to the categories.**

	Survey 1		Survey 2			<b>Total</b>
	Customer	Supplier	Customer	Supplier	Other	
<b>Lack of information</b>	9	2	3	1		15
Abundance of information (complexity)	1					1
<b>Conflicting evidence</b>	7	3	3	1		14
Ambiguity	1					1
Measurement			1			1
Belief						
<b>Communication</b>	11	8	14	2	2	37
<b>Attitude</b>		6	2			8
<b>Limited vision of the whole</b>	6	1				7
<b>Course of action</b>	8	4	9	2	4	27
Database	1		6	2	1	10
<b>Missing knowledge</b>	1	1	4			6

In table 5, the first six rows are Zimmermann's (2000) original classifications. The next rows are new material-driven classifications created by the author. There were no references to beliefs, and also in measurement there was only one reference in the material of the survey. This measurement reference can be handled as a database classification, because in the original text there was a mention about data that was not saved to a database. The reference to abundance of information is very close to the references of conflicting evidence. The reference to ambiguity is also referenced to the classification course of action. Databases are excluded from this research because several earlier studies have focused on maintenance databases and software systems. This research focuses on the seven classifications **bolded** in table 5.

## **Lack of information**

In this research, the notion lack of information is used when information or data is not available at the right time. In the survey one answer described the issue well: “*Typical lack of information is associated with the documentation of equipment. Drawings or other information are not where they should be kept. Usually missing information can be found only by asking somebody who knows.*”

According to the two surveys, lack of information is mainly the problem of the maintenance customer. Customers do not get enough information about details, and things like up-to-date documents and drawings are missing. The missing information can be found at least by the manufacturer of the equipment if nobody else can help. Another problem concerns maintenance software. Software is used, but saving data to the system is not properly done. Sometimes information can be misunderstood because the communication is adequate. This issue is also discussed in the communication section.

However, lack of information is not considered a difficult issue because it can usually be solved quite easily by asking somebody. Of course this will take time and may delay the maintenance process.

## **Conflicting evidence**

Conflicting evidence is usually linked to documentation. In different documents there are totally different values, which should be the same in both documents. These situations are very difficult to clarify because it cannot be easily solved which values are the right ones.

In the survey the following kind of answers were given: “*Problems arise especially in ordering spare parts, there are several different spare part lists and instruction manuals for the same device.*” If you order a wrong spare part for maintenance shutdown, so you may need to lengthen the maintenance shutdown to get the right spare part. In the worst case the situation comes to attention when a spare part must be installed and it does not fit.

Conflicting evidence is a very problematic issue in maintenance. It is very difficult to solve because if you ask for more information, how can you be certain that this new information is right or the information you need? Also the influence of conflicting evidence can be serious.

## **Communication**

Communication was the most frequently cited issue in the surveys. There are both customer and supplier side gaps in communication. “*The biggest problem is the fact that customers have a lack of staff for the maintenance of an attractive site.*” “*Information cannot be applied at the right place.*” “*The exchange of information does not always go smoothly, the work developer does not see the need to report what has been done and the user of the machine stays unsure of the repair of the property.*” There were also mentions about improving communication between the parties: “*Create well-established practices to monitor and improve, as well as for reporting.*” “*A functional and sufficiently tight meeting practice to reduce the information gaps.*”

As the above examples show that communication is a difficult issue, and misunderstandings can occur easily. On the other hand, it can be quite easy to organize meetings and create reports to improve the communication between the parties involved.

### **Attitude**

Attitude is quite difficult to measure or observe. Some examples of what might be classified as attitude were found in the answers, however. “*Often, you do not want to provide the requested information, even though they would benefit from the reliability improvement methods.*” “*Plans do exists and sometimes we have been very close to implementing them, but other things have always taken priority.*” Sometimes attitude problems can be quite close to the next classification, a limited vision of the whole.

### **Limited vision of the whole**

A limited vision of the whole can be seen as an organizational and management problem. Maintenance may have been outsourced, and so there are many different parties operating in the field of maintenance. “*Distribution of own and outsourced maintenance must be clearly expressed, as distinguished from the everyday maintenance of the project design.*”

Another issue is how work is planned to be implemented. Is there enough staff in all the phases, for example in design? “*Preventive maintenance should focus more on resources and enhancing maintenance as well. This could prevent repetitive defects and failures causing excessive costs.*”

### **Course of action**

The course of action is also an organization-related issue. “*The operations have not been described as processes, or they are not followed, we do as we have always done.*”

Maintenance software systems are seen as a solution helping to act as wanted. “*When the workload increases so easily by individual work, the flow of information is left untreated. In this case, the resources are usually concentrated on the most important work, and the less important may be left with less attention. Knowledge production and transfer is the key to system maintenance.*” “*Sharing information between individuals, deciding which information will remain with one person. Information should be obtained directly from systems automatically.*”

### **Missing knowledge**

The problem of missing knowledge is very difficult to solve. Achieving knowledge by training will take a long time. If it is to be achieved by purchasing a service, it may be difficult to find a proper supplier. “*The organizations are fragmented and there are rapid changes, which means that the high turnover of persons in charge causes problems.*”

Table 6 contains a summary of the main results of this paper.

**Table 6. Classifications of problems and solutions to reducing their occurrence.**

<b>Classifications</b>	<b>Solution to reducing the occurrence</b>
Lack of information	The situation is improved by gathering more relevant information from different sources.
Conflicting evidence	An increase of information does not reduce uncertainty. Checking and deleting wrong information might help to transform the situation to certainty.
Communication	Communication problems between people are common. Fortunately meetings are easy to organize.
Attitude	This is a difficult issue to solve, especially when maintenance has been outsourced. Training is needed.
Limited vision of the whole	This is close to the previous and next classifications. More training may be needed.
Course of action	This is quite closely related to attitude and a limited vision of the whole.
Missing knowledge	The needed skills must be acquired.

## 5 Conclusions

The starting point to this research was to find out whether there is any kind of lack of information or knowledge in the area of maintenance. According to the surveys made in the study, there are quite often situations where some information or data is missing, and sometimes also the needed knowledge is not available.

The theory base was originally Zimmerman's (2000) causes of uncertainty. Uncertainty is a situational property of a phenomenon which is influenced by available and required information. Zimmerman's classifications were used as the basis of classifications in this research. It was soon found that more classifications were needed. The new classifications were:

- communication
- attitude
- limited vision of the whole

- course of action
- missing knowledge.

All these new classifications can be considered as outsourcing problems of maintenance. New processes are created but they are not in use. It is not impossible to solve these problems, the solution is just to pay attention and be aware of the possible problems. However, these problems can appear even when maintenance has not been outsourced.

In the surveys, communication was considered to be a relatively easy problem to solve, what is needed is just organizing meetings and using maintenance software systems properly. Communication was considered the most common cause of lack of information. Communication problems can be managed easily, but communication must be paid attention to. Of course, every time two persons talk to each other, some information will be lost.

The next classifications, attitude, limited vision of the whole, and course of action have similar effects. Information will not be moved properly forwards because the people involved think that forwarding information is someone else's responsibility. Attitude can be an individual or organizational problem. A person can think that this task is not my responsibility. Old methods of doing things may be in use in the organization, even when new processes have been adopted. This can be prevented by training, as well as the next two issues. If a person has a limited vision of the whole of what should be done in the company, he or she can cause serious problems. For example, the person does not report a problem in a machine he has noticed because he does not know to whom or how to report about it. The course of action can be quite a similar issue as attitude at the organizational level. New processes should be used, but nobody uses them because these tasks have always been done in a different way.

Missing knowledge is hard to fill. If the needed knowledge is not available in the company, it may try to buy it from suppliers. Then there are also timing problems if the needed resource is not available at the right time.

*“In my opinion the information gaps are usually due to the company’s own actions, as the service provider acts according to the operation model required by the company. The model of knowledge transfer is not documented adequately and it is not a written form of action.”*  
*“Information gaps could be avoided by regular exchange of thoughts, and not by making contact when problems have already risen. We should be interested in what the others are doing and share information.”* According to the surveys, information gaps can be quite easily reduced by regarding the potential problems of data transmission.

Further research is needed to compare the differences between successful data transmission and unsuccessful cases. In this research only unsuccessful cases were included and successful cases were not considered.

Also maintenance and knowledge management research combining information management and maintenance is needed. There are several studies dealing with maintenance software and databases, but not many about information and knowledge management in maintenance.

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## **Publication II**

Metso, L., Marttonen, S., Thenent, N., and Newnes L.  
**Adapting the SHEL model in investigating industrial maintenance**

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# Adapting the SHEL model in investigating industrial maintenance

Lasse Metso and Salla Marttonen, LUT School of Business and Management, Lappeenranta University of Technology, Lappeenranta, Finland, and

Nils E. Thenent and Linda B. Newnes, Department of Mechanical Engineering, University of Bath, Bath, UK

## Abstract

**Purpose** – The purpose of this paper is to identify and categorize problems in knowledge management of industrial maintenance, and support successful maintenance through adapting the SHEL model. The SHEL model has been used widely in airplane accident investigations and in aviation maintenance, but not in industrial maintenance.

**Design/methodology/approach** – The data was collected by two separate surveys with open-ended questions from maintenance customers and service providers in Finland. The collected data was coded according to SHEL model -derived themes and analysed thematically with NVivo.

**Findings** – The authors found that the adapted SHELO model works well in the industrial maintenance context. The results show that the most important knowledge management problems in the area are caused by interactions between Liveware and Software (information unavailability), Liveware and Liveware (information sharing), Liveware and Organisation (communication), and Software and Software (information integrity).

**Research limitations/implications** – The data was collected only from Finnish companies and from the perspective of knowledge management. In practice there are also other kinds of issues in industrial maintenance. This can be a topic for future research.

**Practical implications** – The paper presents a new systematic method to analyse and sort knowledge management problems in industrial maintenance. Both maintenance service customers and suppliers can improve their maintenance processes by using the dimensions of the SHELO model.

**Originality/value** – The SHEL model has not been used in industrial maintenance before. In addition, the new SHELO model takes also interactions without direct human influence into account. Previous research has listed conditions for successful maintenance extensively, but this kind of prioritization tools are needed to support decision making in practice.

**Keywords** - Knowledge management, Information management, Qualitative data analysis, Industrial maintenance, SHEL, SHELO

**Paper type** Research paper

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## 1 Introduction

Complex organizational structures, a multitude of disciplines and several reporting levels are often identified as problems in the maintenance function (Swanson, 2003). Tendencies towards integrated product and service offerings increase such complexity further (Pawar et al., 2009). Within the maintenance function, personnel with different skill sets, such as electricians, mechanics and pipe installers need to work together, and the management has to take this into account (Organ et al., 1997). In addition to organisational and managerial complexities, maintenance faces complexity related to technical and human learning aspects (Shafiei-Monfared and Jenab, 2012). All these together make resource allocation and work scheduling in maintenance a difficult task. Accordingly, computer support has become indispensable for stock control, management of personnel, task tracking, processing of historical data, document change control, etc. (Waeyenbergh and Pintelon, 2002). Therefore, more attention must be paid to information processes to support the ability to make decisions that are appropriate in the situation at hand and take account of longer-term consequences without neglecting the crucial role human knowledge plays in maintenance. Decreasing the complexity of organisational structures or maintenance tasks are strategies for reducing the requirements of information processes (Swanson, 2003; Shafiei-Monfared and Jenab, 2012). Other strategies aim at increasing the capacity of an organization's information processing capability either by investing into information systems or by streamlining the decision making processes (Swanson, 2003; Crespo Marquez and Gupta, 2006), and integrating the maintenance function with other companies' activities through advanced IT systems (Sherwin, 2000). However, it is recognised that to support effective decision-making, the better the understanding of a problem the more successful the proposed solution can be (Triantaphyllou et al., 1997). For the investigation of the challenges in industrial maintenance, methods are required that can capture the multitude of different influences on successful maintenance, such as humans, technical systems and organisational settings (Thenent et al., 2013). Metso (2013) has identified problems in information sharing as well as lack of information in industrial maintenance. However, no guidance or good practises for how to overcome these challenges have been proposed. Thenent et al. (2013), having investigated the conditions for successful maintenance suggest that the SHEL model offers potential for improved understanding of maintenance practices and conditions for successful maintenance. By combining these two perspectives in this paper (see Figure 1), we shed light on the information management challenges that arise in industrial maintenance from the interactions between the different elements in this complex system.

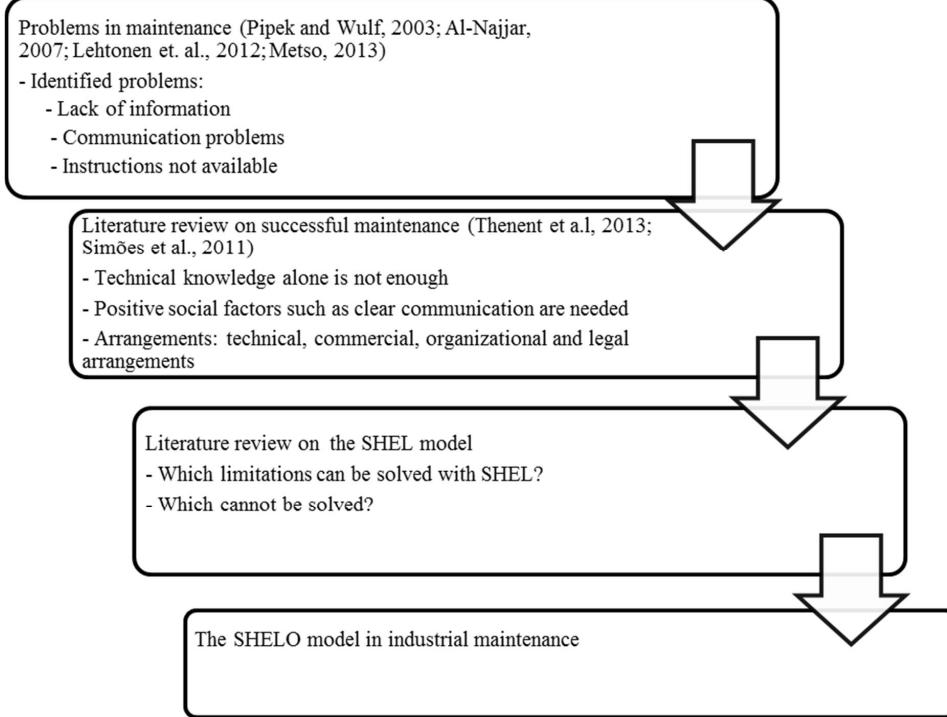


Figure 1. Phases of adapting the SHEL model in industrial maintenance

The SHEL model is a framework that can be used to study the interactions between individuals, the systems in which they function, and the environment which influences the individuals' activities (Hawkins 1987). Edwards (1972) presented the SHEL model which comprises three elements that interact with humans (called Liveware): Software, Hardware and Environment. Hawkins (1993) added the person-to person relationship (Liveware – Liveware) and called the resulting model SHELL. Hawkins focused on relationships between Liveware and Software, Liveware and Hardware, Liveware and Environment, and Liveware and Liveware. The SHELL model does not cover the relationships between Hardware-Hardware, Hardware-Environment, and Software-Hardware. Chang and Wang (2010) added the organizational element to the model and called it SHELO.

The SHEL model is used in aviation in accident investigation and in aviation maintenance (see for example Licu et al., 2007; Edwards, 1981; Lufthansa, 1999) Other applications of the SHEL model include maritime organisations (Chen et. al., 2013). This paper demonstrates an application of a modified SHEL model in industrial maintenance. In this paper industrial maintenance includes:

- planned maintenance actions;
- unplanned repairs;
- calibration and testing;

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- definition, planning, management and improvement of maintenance actions;
- internal and external collaboration between organisational units involved in industrial maintenance activities.

A key problem for service providers of maintenance is managing the ever-increasing information flow and system complexity. There is an increasing amount of digital product information and other data provided together with hardware and software products from manufacturers, subsystem suppliers and other sources (Candell et al. 2009). Attempts to resolve the challenges related to information sharing and communication between different parties in industrial maintenance include the implementation of advanced software solutions, such as Product Lifecycle Management Systems (Lee et al., 2008) and e-maintenance (Candell et al., 2009). However, as recognised by O'Dell et al. (1998), while software helps in information collecting and sharing, it does not solve all problems. Brax and Jonsson (2009) observed that maintenance management software was not frequently used in the setting they investigated, and the maintenance management software did not support automated data processing tools. The companies also suffered from a lack of business intelligent tools. Furthermore, fragmented maintenance information caused problems such as shipping of incorrect spare parts. In addition, feedback from customers was not gathered, which gave the impression that the company lacked interest in its customer. Even lack of trust between the provider and its clients prevented successful collaboration. Communication between the different parties is one part of maintenance management. The correct management of maintenance information helps to develop the planning and scheduling of maintenance. This information is collected from the maintenance process and other relevant information (Barberá et al., 2012).

Within condition-based maintenance, the condition of the technical system is monitored and combined with fault diagnosis to support decision making about the appropriate maintenance interventions. While the amount of collected data can be huge, it needs to be converted into useful form (Campos, 2009). Remote diagnostics has been used to collect data from customers' products and plants. A customer usually has staff with limited knowledge, and thus outside service support is needed. Data about a machine and its working environment is needed at any time. This information can be shared with other users, and also with service providers as well as inside the company. More research is needed on how to manage the information and distributed decision making (Lee, 1998).

The literature reveals that challenges in industrial maintenance tend to be tackled mainly through the implementation of more sophisticated IT systems and an increase of available data. However, frequently overlooked are the interdependencies of different elements involving human, organisational and technical factors that create the conditions for maintenance to be successful. The diversity of these elements is best approached through a qualitative data analysis which enables the integration of traditionally non-commensurable observations. We propose the use of the SHEL model in identifying the challenges in information processing in industrial maintenance to support the information flow within the maintenance function and between maintenance and other functions.

The literature review on successful maintenance and problems in industrial maintenance showed that all SHEL elements play a role in them. The analysis of the collected data showed which elements of the SHELO model and which relationships are relevant in industrial maintenance. The contribution of this paper is a novel application and an extension of the original SHEL framework, focusing on identifying the most problematic aspects of maintenance knowledge management.

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The remainder of this paper is structured as follows. Section 2: A literature review on the conditions for successful maintenance and an introduction to the SHEL model and its application; Section 3: An outline of the research methodology, including a description of the methods of data collection and data analysis using a modified SHEL model that incorporates organisational factors. Hence, it is named SHELO; Section 4: Findings are presented that demonstrate that the elements captured by the SHELO model and their relationships are suitable for capturing challenges in industrial maintenance; Section 5: Conclusions that highlight the value of the SHELO model in understanding the challenges in industrial maintenance and outlines further work aiming at developing means of supporting decision-making based on the findings of the study.

## 2 Literature review

Maintenance can impact many aspects significant for business, for example equipment downtime, quality and productivity (Shyjith et al., 2008). Here we define that for maintenance to be successful, the targeted availability must be achieved when required (Thenent et al., 2013). This is not a simple goal and requires a systemic approach, because a lot of different elements connected to each other with causal relations affect the outcome. These elements include e.g. people, machines and equipment, computers, software, and the environmental context. The importance of the competence of the personnel and training for successful maintenance has been acknowledged by many scholars (e.g. Al-Najjar, 2007; Al-Najjar and Alsyouf, 2003; Goetsche, 2005; Simões et al., 2011).

The number of maintenance outsourcings has been increasing (Taracki et al., 2009; Xia et al., 2011) despite the difficulties involved in measuring and evaluating the viability of a strategic decision to outsource (Gómes et al., 2009). In addition to outside service providers, also the original equipment manufacturers are increasingly interested in taking their own share of the maintenance business and shifting from a product-oriented business strategy to a service-oriented one. According to Candell et al. (2009), a service-oriented strategy requires harmonization of the maintenance process. In general, the networking development introduces new challenges for communication and cooperation, even within the same organisation in making maintenance successful. For example, information exchange between technicians and equipment operators is of utmost importance in maintenance (Aubin, 2004; Kinnison, 2004; Leney and Macdonald, 2010; Reiman, 2010).

### 2.1 Conditions for successful maintenance

Maintenance management is facing fundamental changes with the emergence of the industrial internet (or internet of things) (see e.g. Wang et al., 2013). These changes include an expected increase of information flow, which leads to the development of more complex and technologically advanced information systems. These challenges, combined with the networking trend and the overwhelming amount of data can lead to

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severe problems with fragmented data due to lack of communication between people, organizations and technological systems (e.g. Candell et al., 2009; Ranasinghe et al., 2011).

The challenges and requirements of successful maintenance can be studied on different levels, from operative maintenance of single assets to strategic management of maintenance in companies or company networks. To address this variety, Table 1 below shows two different perspectives on the required conditions for success in maintenance. The left column lists the major elements to be discussed in a single maintenance contract according to standard SFS-EN 13269 (2006), while the right column presents the requirements for designing, implementing and maintaining asset management systems as listed in standards ISO 55000 (2014) and ISO 55001 (2014).

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**Table 1.** Conditions for successful maintenance from the perspective of single contracts and on the system level (ISO 55000, 2014; ISO 55001, 2014; SFS-EN 13269, 2006)

MAINTENANCE CONTRACT LEVEL REQUIREMENTS	ASSET MANAGEMENT SYSTEM LEVEL REQUIREMENTS
<ul style="list-style-type: none"> <li>▪ Determining the parties and their intentions</li> <li>▪ Defining the main technical, commercial and legal terms</li> <li>▪ Recognising the scope of the maintenance, e.g.: <ul style="list-style-type: none"> <li>- operation and maintenance location,</li> <li>- task content,</li> <li>- time schedule,</li> <li>- impediments and delays</li> </ul> </li> <li>▪ Agreeing on the technical arrangements, e.g.: <ul style="list-style-type: none"> <li>- verification,</li> <li>- technical information of the equipment,</li> <li>- supply of spare parts, materials and consumables</li> </ul> </li> <li>▪ Settling the commercial arrangements, e.g.: <ul style="list-style-type: none"> <li>- prices and terms of payment,</li> <li>- warranties and incentives,</li> <li>- penalties/liquidated damages,</li> <li>- insurances and financial guarantee</li> </ul> </li> <li>▪ Making the organisational arrangements, e.g.: <ul style="list-style-type: none"> <li>- providing conditions for performance,</li> <li>- health and safety specifications,</li> <li>- environmental protection,</li> <li>- security specifications,</li> <li>- quality assurance,</li> <li>- supervision/management,</li> <li>- keeping records, documentation</li> </ul> </li> <li>▪ Agreeing on the legal arrangements, e.g.: <ul style="list-style-type: none"> <li>- property rights and copyrights,</li> <li>- confidentiality,</li> <li>- force majeure,</li> <li>- liabilities,</li> <li>- settlement of disputes,</li> <li>- reasons and formalities for termination</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>▪ Defining the context of the organisation: <ul style="list-style-type: none"> <li>- external and internal issues,</li> <li>- the needs and expectations of stakeholders,</li> <li>- interaction with other management systems,</li> <li>- the asset portfolio covered by the system,</li> <li>- asset management strategy</li> </ul> </li> <li>▪ Providing leadership: <ul style="list-style-type: none"> <li>- leadership and commitment (e.g. integration to business, ensuring resource availability and communication),</li> <li>- asset management policies,</li> <li>- organisational roles, responsibilities and authorities</li> </ul> </li> <li>▪ Good planning: <ul style="list-style-type: none"> <li>- actions to address risks and opportunities,</li> <li>- establishing asset management objectives and ways to achieve them</li> </ul> </li> <li>▪ Ensuring support: <ul style="list-style-type: none"> <li>- required resources, competence and awareness on e.g. policies, performance and risks,</li> <li>- internal and external communication,</li> <li>- information requirements and documentation</li> </ul> </li> <li>▪ Operations management: <ul style="list-style-type: none"> <li>- operational planning and control,</li> <li>- management of change,</li> <li>- management of potential outsourcing</li> </ul> </li> <li>▪ Organising performance evaluation: <ul style="list-style-type: none"> <li>- monitoring, measurements, analyses and evaluations,</li> <li>- internal audits and top management reviews</li> </ul> </li> <li>▪ Striving for improvement: <ul style="list-style-type: none"> <li>- corrective and preventive actions,</li> <li>- continual improvement</li> </ul> </li> </ul>

Based on Table 1, on the level of single maintenance contracts the requirements seem to be technical by nature, whereas on the strategic system level the focus is more on communication and management. Overall, it can be concluded that the complex, diversified characteristics of maintenance call for systemic methods both in research and in actual maintenance management. In addition, maintenance is highly dependent on the decisions and competence of the personnel (Simões et al, 2011). To study the relationship of these human factors and the maintenance environment we have adapted the SHEL model in analysing our data on maintenance knowledge management, as suggested by Thenent et al (2013).

## 2.2 The SHEL model

Developed by Edwards (1972), the SHEL model is named after the initial letters of its elements Software (S), Hardware (H), Environment (E) and Liveware (L). The three elements ‘L’, ‘H’ and ‘S’ interact with each other and all of them interact with ‘E’, the environment. The relations are according to Edwards (1972): L, L-S, L-H, and L-E. The difference between L and L-L is that L-L signifies human interactions while Hawkins (1987) describes the characteristics of the central L in the SHELL model in engineering terms as:

- Physical size and shape
- Fuel requirements (food, oxygen, water)
- Input characteristics (senses)
- Information processing
- Output characteristics
- Environmental tolerances

Also psychological aspects, such as biases, mental conditions etc., as well as education and training can be seen as L elements. The term “Software” (S) is used to describe the rules, regulations, orders, laws, and procedures that govern the execution of tasks. “Hardware” (H) stands for physical features such as tools, material, objects, and equipment. As such, the ‘L-H’ combination denotes interactions of humans with technical systems. The environmental context ‘E’ represents for example the temperature, weather and noise the human is exposed to. Finally, the humans involved in the tasks are represented by ‘L’ as Liveware.

Hawkins (1987) introduced an evolution to the original SHEL model with the addition of a second L to place a stronger focus on the human side. While the new model captures all relations exhibited by the SHEL model, an L-L interface was added to reflect the interactions between humans. This L-L relation can for example capture interpersonal dynamics of flight crew functions as a group, leadership, crew cooperation and team-work. This way the SHELL model can capture relations of humans with other humans as well as interactions with the environment, machines (Hardware) and procedures or documentation (Software).

SHELL-Team represents a further evolution in which collaboration and communication with participants from distant locations or co-operative working in common contexts have been added (ICAO, 1997). The SHELL-Team (or SHELL-T) is applied in aviation maintenance tasks and process planning. In the area of nuclear power generation, Kawano (1997) found that the SHEL model was suitable for the explanation of human factors, team work and organizational effects. However, management factors such as organization, administration, safety culture etc., were considered not to be captured appropriately by the SHEL model. Therefore, Kawano (1997) proposed the m-SHEL evolution, where ‘m’ describes management factors separately from the other elements.

A systematic process for the investigation of human factors in seafaring has been presented by the International Maritime Organization (IMO). This process uses the SHEL model as a framework in addition to the Accident Causation and generic error-modelling system GEMS and Taxonomy of Error (IMO, 1999). Chen et al. (2013) use the SHEL model to describe preconditions in the Human Factors Analysis and Classification System for Marine Accidents (HFACS-MA).

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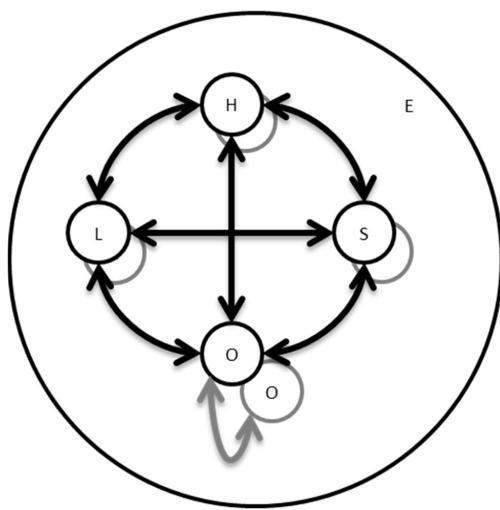
The International Civil Aviation Organization (ICAO) highlights the organizational issues of airline maintenance operations (ICAO, 1998). Also the International Air Transport Association (IATA, 2006) defines five categories in the accident classification system: human, technical, environmental, organizational, and insufficient data. Chang and Wang (2010) have presented a new human-organization component and added it to the SHELL model. Hence, the resulting SHELL model incorporates a new interaction between the Aircraft Maintenance Technician (AMT) and the organisation, Liveware-Organisation (L-O). The interactions captured by the SHELL model comprise: L, L-S, L-H, L-E, L-L and L-O (Chang and Wang, 2010).

Cacciabue et al. (2003) have developed a model and simulation of the task performance of an AMT which combines the existing SHELL and RMC/PIPE (the Reference model of Cognition / Perception, Interpretation, Planning and Execution) models. RCM describes the cognitive and behavioural performance of human beings interacting with machines, using the four cognitive functions specified by PIPE. The simulator can be used in the development of AMT training programs and for the creation of maintenance procedures. The different dimension captured in the outlined SHELL model variations are listed in Table 2.

**Table 2.** Comparison of SHEL, SHELL, m-SHEL, and SHELL model

Edwards (1972) SHEL	Hawkins (1987) SHELL	Kawano (1997) m-SHEL	Chang & Wang (2010) SHELL
L	L	L	L
L-S	L-S	L-S	L-S
L-H	L-H	L-H	L-H
L-E	L-E	L-E	L-E
L-L		L-L	L-L
		m	
			L-O

In industrial maintenance, human factors and other aspects that are not included in the original SHEL model, such as the organisations involved play a role (Chang and Wang, 2010). Unlike all the evolutions of the SHEL model discussed above, as shown in Table 2, we propose a model that is not focused on the interactions between humans and the other elements, i.e. human factors only. Hence, our model, called SHELO, can capture dimensions linking all elements to each other, as shown in Figure 2. For example, maintenance can be outsourced to an external service provider, which is reflected in the O-O dimension. Even more specifically, different computerised maintenance management systems (CMMS) may be in place in different organisations, and such a situation can be categorised by the S-S element. Accessibility to IT systems would fall under L-H interaction, the computer being the H (Hardware) and the user the L (Liveware).



**Figure 2.** The SHELO model.

Table 3 shows further examples of relevant factors in industrial maintenance and how they are categorised in the SHELO model.

**Table 3.** The contents of elements in industrial maintenance

Content in industrial maintenance	
<b>S Software</b>	Maintenance procedures Installation instructions Plans and schedules (Automated) algorithms of condition monitoring Regulation (regarding e.g. pressure vessels, nuclear power plants etc.) Warranty clauses
<b>H Hardware</b>	Tools Materials Objects Equipment Computers Buildings / Physical infrastructure
<b>E Environment</b>	Environmental context Temperature, Noise Economic environment
<b>L Liveware</b>	Humans (operators, maintenance technicians, managers, designers, etc.) People interaction (L-L) Personal attitude Skills and education Availability of personnel
<b>O Organisation</b>	Organisational structure

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### 3 Methodology

The research methodology used in this paper comprises two surveys for data collection and qualitative means to analyse the survey data. The steps of conducting the research are depicted in Figure 3 and explained in more detail below.

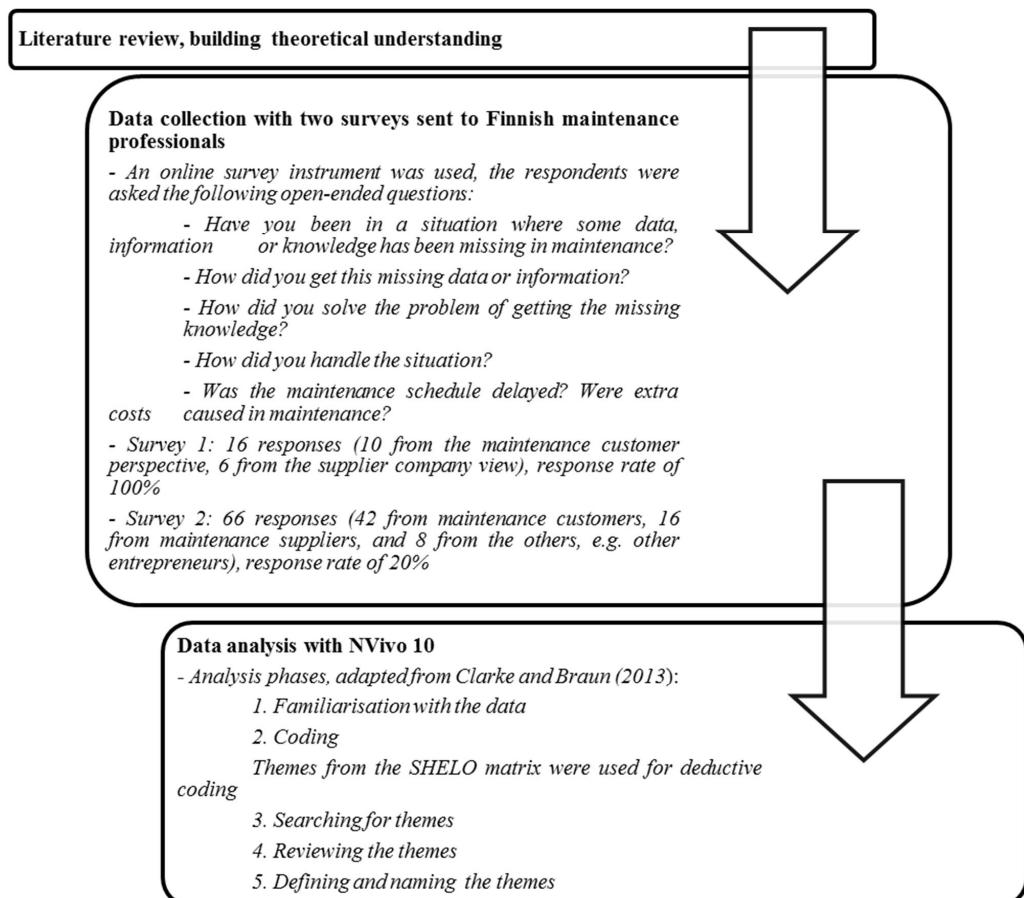


Figure 3. The phases of the conducted research

The survey questions were originally designed around information management and the identification of information gaps in industrial maintenance. The data collected for the study included in total 82 responses to two separate surveys from maintenance customers and service providers. The first survey was sent to 16 Finnish maintenance professionals who participated in updating education at Jyväskylä University of Applied Sciences. Completing the survey was required in order to pass one of the respondents' courses, so

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a response rate of 100% was achieved. The second survey was sent to 327 professionals from 241 member companies of the Finnish Maintenance Society, Promaint. In the second survey a response rate of 20% was achieved, resulting in 66 complete responses. While the two surveys were separate, the questionnaires were similar for all participants. The answers to the open-ended questions were coded and thematically analysed with NVivo version 10 software.

#### 4 Findings – the SHELO model in industrial maintenance

Applying the SHELO model to the survey data showed that the L-S, L-L, L-O and S-S themes presented in Table 4 comprised the highest number of coded text passages. There were no codes in the elements S-E, H-E, H-O, E-E, H and E. One explanation for this is that the survey questions did not explicitly touch on aspects such as the environment, organisations or Hardware -related concepts, such as tools and materials.

**Table 4.** The SHELO dimensions and number of codes for each category

	S	H	E	L	O
<b>S</b>	34	S-S 0			
<b>H</b>	1	S-H 2	H-H 6		
<b>E</b>	0	S-E 0	E-H 0	E-E 0	
<b>L</b>	4	L-S 31	L-H 7	L-E 2	L-L 31
<b>O</b>	2	S-O 6	O-H 0	E-O 1	L-O 23
				O-O 7	

Tables 5 to 9 (and in appendix A) show results that emerged when employing the SHELO model in coding the survey answers. As the survey contained open questions, some answers were quite long and Tables 5 to 9 show what we consider the most insightful results. The hits on dimension L, Liveware, were mainly related with attitude. More details about the results of this element can be seen in Table 5 below.

**Table 5.** Liveware (L) findings

L (Liveware)
<b>Misunderstandings cause information breakdowns because the other parties do not understand the criticality of the situation. Another issue is misunderstandings about the schedules and the scope of the service.</b>
<b>The priorities of the maintenance tasks are inadequate. Each group considers only their own point of view to the maintenance, and no one wants to take overall responsibility or provide it to others.</b>
<b>Due to the hectic pace, things stay untreated.</b>
<b>When the workload increases, the information exchange is not done properly.</b>

The total amount of codes in the L-S element was 33. Table 6 shows a selection of six replies that were considered representative for the codes in this element. The L-S codes typically highlight a lack of information, information that was not updated, or information that was available but could not be found when needed. Other aspects concern instructions that were not updated or improper documentation. Ideas

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for improvements comprised meetings, co-operation and network between the organisations/individuals involved.

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**Table 6.** Liveware-Software ( L-S) findings

L-S (Liveware – Software)
<p><b>It is difficult to find information about equipment, such as dimensions, design of past projects.</b></p>
<p><b>Maintenance Instructions were not up-to-date.</b></p>
<p><b>Customers could not provide the error messages of the production machines because information was not available.</b></p>
<p><b>The recorded information such as fault information is inadequate or unreliable.</b></p>
<p><b>The downtime work is not scheduled or the schedules do not include all tasks required.</b></p>
<p><b>Maintenance procedures are not documented precisely.</b></p>
<p><b>Required information such as plans and schedules are not easily available or the information is unreliable.</b></p>
<p><b>Schedules are not known early enough.</b></p>
<p><b>Required production information is not recorded in the CMMS system.</b></p>
<p><b>To acquire the information required to solve a problem, additional communication or interviews with service providers are needed.</b></p>
<p><b>The maintenance tasks are not described as processes, or instructions are not followed. Work is done the way it has always been done. This could be prevented by acting according to agreed uniform processes.</b></p>
<p><b>Information is usually available in some place, but not found.</b></p>
<p><b>Equipment registers do not point to the right serial number of the equipment.</b></p>
<p><b>The information sharing process is not documented.</b></p>
<p><b>Several times:</b> Maintenance tasks are carried out according to the information available and may require reworking when more information becomes available.</p>
<p style="text-align: center;"><b>Respondents' suggestions for improvements</b></p>
<p><b>Co-operation with other maintenance partners should be improved to avoid information gaps.</b></p>
<p><b>Work planning is in an essential role in collecting information. The anticipation (of what) and preparation well in advance eliminates the problems of access to information.</b></p>
<p><b>Information can be found by networking with all maintenance partners.</b></p>
<p><b>Equipment registers should be exact and contain sufficient information.</b></p>

The most prominent challenge identified in the L-L (Liveware – Liveware) element was related to individual's attitudes. Furthermore, communication problems were described, including a lack of information sharing between individuals. More details are shown in Table 7.

**Table 7.** Liveware-Liveware ( L-L ) findings

L-L (Liveware – Liveware)
<p><b>Communication between the customer and the supplier is important. Too distant attitude towards each other breaks the information flow.</b></p>
<p><b>The customer is unwilling to provide the information required.</b></p>
<p><b>Functional and compact meeting practice reduces information gaps. Emails and the use of production logs as an information channel reduces the impact of data outage.</b></p>
<p><b>Several times:</b> Lack of communication and instructions:</p>
<ul style="list-style-type: none"><li>– Something must be done without sufficient information</li><li>– When information is available, changes to the maintenance done are required to complete the task.</li></ul>
<p><b>The needed information is kept by a single person.</b></p>

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As depicted in Table 8, the L-O element revealed problems in communication between people from different organisations or departments, as well as areas of unclear responsibility. Ideas for improving communication included greater flexibility between departments and autonomy to identify and implement solutions that support information sharing.

**Table 8.** Liveware – Organisation ( L-O ) findings.

L-O (Liveware – Organisation)
<b>Unclear responsibilities for example about spare parts, modifications and how systems are maintained.</b>
Communication problems when information is passed through too many levels in the organisation. Maintenance support is not reachable. Rush and lack of resources can cause a situation in which it is assumed that everybody involved knows everything that is required. Customers do not know the reasons for equipment malfunction. <i>Several times:</i> Changes in personnel e.g. the contact person, cause a lack of information as well as faceless trading.
<b>Respondents' suggestions for improvements</b>
Add flexibility between departments to improve communication. Encourage personnel to identify and take advantage of new solutions. Problems could be easily reduced by improving communication with the maintenance service providers. The maintenance service provider has to be selected carefully by the customer. In addition, the work should be defined precisely. Problems in information sharing can be avoided by organising information sharing and the use of CMMS systems.

The S element concerns concepts related to procedures and information processing through computer systems. A typical problematic situation in the S element was wrong or incomplete information. The most important improving idea was to verify data when entering it into a CMMS system. Further findings are presented in Table 9.

**Table 9.** Software (S) findings

S ( Software)
<b>The importance of smooth routine maintenance to avoid the workload of maintenance designers.</b>
<b>Lack of spare parts due to a missing purchase order.</b>
Maintenance software systems are often bought with an ERP system and do not fulfil the needs of the maintenance personnel. Not enough history data available on the maintenance system The statistics of defect data is unreliable. IT interface challenges, for example connecting to the maintenance target with CMMS when wireless data transmission is forbidden for safety reason, and no other IT connection is available. Documentation is not updated, for example a spare part list of a new machine was not updated and only the older machine version's spare part list was available. Difficulty in ordering spare parts because the equipment has many different spare part catalogues and manuals. Difficulty to provide comprehensive and precise information in the reporting system. Maintenance costs contain also other than maintenance work.

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**Required production information is not recorded in the CMMS system.**

*Several Times: Needed data is not available in the maintenance system*

**Respondents' suggestions for improvements**

**A mobile maintenance software system would help prevent lack of information. The system could be easily implemented with customers.**

**In the maintenance software system it is essential to enter the data into the system, verify the data, take advantage of the data and deliver the data to everybody.**

**Setting clear priorities and focusing on important maintenance tasks accompanied by good instructions will raise the quality of maintenance work.**

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The results of the elements L-H, L-E, S-H, S-O, H-H, H, E-O, O-O and O are presented in appendix A due to the small number of codes for them. Element L-H with 8 codes received the highest number of codes for the elements presented in appendix A. Even though there were important aspects, such as communication and insufficient information, we focused on the elements with a higher number of codes.

Using the SHELO model as a basis for coding was shown to provide useful insights into the challenges in industrial maintenance. While previous research using the same data (Metso 2013) highlighted challenges in communication and information sharing, application of the SHELO model provided insights into how other influencing factors such as organisations and individuals relate to each other. In addition, the SHELO model was able to incorporate such findings as the challenges related to procedures and IT systems (S-S) that would have remained hidden in the original SHEL model due to the lack of direct human (L) interaction. This way the SHELO model can provide a novel perspective on industrial maintenance to account better for the diversity of influencing factors when making decisions on maintenance practices.

## 5 Conclusions

This paper demonstrates the application of a modified SHEL model to analyse survey data about information and knowledge management in industrial maintenance. To the best of the authors' knowledge this is the first application of the SHEL model in such a context. While the original SHEL model was created to investigate human factors in accidents, we adapted the model to capture organisational factors as well, and that is why our model is called SHELO. The SHELO model, unlike the other variations of the SHEL model, takes interactions without direct human influence into account. Such variation is useful in modern maintenance management and the related research, because more and more information is transferred and processed without direct human interaction. Our analyses show that the most relevant knowledge management problems in industrial maintenance are in the following areas:

- Interactions between humans and procedures and IT systems, categorised as Liveware-Software within the SHELO model, with emphasis on the unavailability of information;
- Interactions between humans, Liveware-Liveware, where the emphasis is on communication and attitudes towards information sharing;
- Humans as Liveware and Organisation, which comprises communication between organisations and departments and their respective responsibilities;

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- Software, including procedures and IT systems that provide incomplete or flawed information.

The SHELO model proved to be a useful framework for analysing industrial maintenance systematically. It allows categorising identified problems to conduct further analyses on specific problem areas and to identify appropriate solutions. The SHELO model in industrial maintenance shows that problems of knowledge management can be identified by analysing survey data with categories captured by the SHELO model. In addition to problems, we identified propositions for improving maintenance activities and knowledge management in industrial maintenance. Problems in information sharing can be reduced by improving communication with service providers and using CMMS systems. While the existing literature and standards list an extensive number of conditions for successful maintenance, in practice prioritisation tools are needed to support the decision making. Applying the SHELO model can assist maintenance service customers, suppliers and designers in improving maintenance processes and planning.

The research was limited to the identification of information gaps and information sharing problems, as this was what the surveys were originally designed for. For example, environmental and organisational issues were not explicitly raised in the survey questionnaire. In future research, a case study could be executed, capturing an industrial maintenance provider and a customer in the same project to identify whether problems and suggestions for improvement differ between the organisations involved. Furthermore, a new survey specifically designed around the SHELO elements can be employed to gain a broader understanding of the current challenges in industrial maintenance, either in a specific sector or across sectors.

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## 7 Appendix A

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### L-H (Liveware – Hardware)

Needed information should be recorded centralised to software which everybody who needs information can have access to, and also the search function is user-friendly.

CMMS system is available but not properly used.

Spare part availability information should be in a system with easy access.

Customers do not know how to use the ERP systems' maintenance parts effectively.

CMMS system's effective use.

Taking part in equipment replacement projects would be beneficial for maintenance workers to learn about the specific equipment maintenance.

Poor usability of CMMS, which means the relevant data cannot be entered by the maintenance personnel.

### L-E (Liveware – Environment)

Focus on finding out causes, not finding out who is guilty.

Machines were in motion and the quality was just tolerable. The daily work was only fixes and controls.

### S-H (Software – Hardware)

Spare part lists were not available

Needed information must be searched from files, documents, archives, supplier, designers, etc.

### S-O (Software – Organisation)

The customer and maintenance service provider do no enter data to the CMMS systems properly.

A wide own organisation helps to find needed information from own data sources.

The customer and service provider must have data exchange instructions.

Customers cannot find the right information because it is not available.

Information is usually provided by our own company or by the equipment supplier. Sometimes maintenance work is carried out according best information available, requiring subsequent modifications frequently.

When the maintenance service is organised by several maintenance suppliers, lack of information is common. For example, the customer might change the schedule or the content of maintenance without informing the other parties.

### H-H (Hardware – Hardware)

Reports from the supplier are not transferred to the CMMS.

The customer and supplier have different CMMS systems.

Instructions are located in different software systems.

*Several times:* Problems with software systems.

### H (Hardware)

During the maintenance work a design error was found.

### E-O (Environment – Organisation)

More attention should be paid to preventive maintenance.

### O-O (Organisation – Organisation)

Responsibility between the organisations is not clear.

There are many parties involved in maintenance projects. They do different software systems and too many people take part in maintenance. Also financing can be from a different organisation.

Many organisations have different kinds of information in maintenance.

A long approvals chain

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**Fragmentation in organisations and rapid changes.**

**The customer's maintenance does not support multi-vendor networks.**

**The customer has not been aware of the scheduling of production line maintenance.**

**O (Organisation)**

**The supplier's spare part services are available only during office hours, so it can take some time to get help.**

**The operational models are not designed for a multi-vendor environment.**

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## **Publication III**

Metso, L., Marttonen-Arola, S., Ali-Marttila, M., Kinnunen, S-K, and Kärri, T.  
**Identifying fleet data sharing needs, problems and benefits with the Shelo model**

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# Identifying the sharing needs, problems and benefits of fleet data with the Shelo model

Lasse Metso<sup>1</sup>; Salla Marttonen-Arola<sup>2</sup>; Maaren Ali-Marttila<sup>3</sup>; Sini-Kaisu Kinnunen<sup>4</sup>; Timo Kärri<sup>5</sup>  
[lasse.metso@lut.fi](mailto:lasse.metso@lut.fi); [salla.marttonen-arola@lut.fi](mailto:salla.marttonen-arola@lut.fi); [maaren.ali-marttila@lut.fi](mailto:maaren.ali-marttila@lut.fi); [sini-kaisu.kinnunen@lut.fi](mailto:sini-kaisu.kinnunen@lut.fi); [timo.karri@lut.fi](mailto:timo.karri@lut.fi)

<sup>1,2,3,4,5</sup> Industrial Engineering and Management, LUT School of Business and Management, Lappeenranta University of Technology  
Lappeenranta, Finland

## Abstract

In this paper, the SHELO model is used for understanding the most critical data and information management problems and opportunities in the fleet environment. Due to the scattered nature of fleets and the data related to them, there is extensive untapped potential in processing and upgrading the accumulated fleet data into knowledge that can be used in decision making. So far inter-organizational data sharing has not been widely adopted in practice, and thus the full possibilities of fleet management are not yet known.

In this paper, the data has been collected by interviews of people from 4 different divisions of an original equipment manufacturer, and from 3 customer companies who use the product. The first problem identified was who owns the data collected by the product. If the supplier could get this data, it could develop the product and possibly analyse the need of maintenance on the fleet level. A group of similar kinds of assets can be viewed as a fleet, and there are various advantages when the data related to the fleet of assets can be utilized in asset management. Currently the supplier cannot utilize the fleet data to these purposes. The extent of data sharing is now considered case by case. There are no clear rules to sharing data, but the companies can see the potential advantages.

In order to improve fleet management practices, and information and data sharing needs, the problems and benefits are analyzed with the SHELO model. Identifying the problems systematically is an undeniable prerequisite for preventing them.

## Keywords

*Information management, data management, data sharing, fleet, SHELO, qualitative data analysis*

## I. INTRODUCTION

The purpose of paper is to identify the data sharing needs, problems and benefits in the fleet environment. A fleet can be seen as a group of similar kinds of assets. Generally, the term fleet has been associated with aviation and navy contexts, but other asset groups (e.g. industrial production machinery and equipment) can also be considered as fleets, and similar kinds of management practices can be applied [1,2]. The technical and economic data on geographically scattered fleets is vast, multifaceted, and usually fragmented to various companies. It is

not feasible for each company to process all of the data by themselves. Hence, data sharing would have several positive impacts on business, e.g. through motivating collaborative decision making, increasing transparency from the provider side etc. However, companies are worried about sharing too much data.

The SHELO model has been widely used in airplane accident investigations and in aviation maintenance to identify the causes of accidents systematically. The SHELO model [3] has been developed from the SHEL model. With the SHELO model, possible problems, threats and potentials are classified in order to elicit proposals for improvements. The SHELO model has been used previously to find out the most important knowledge management problems in industrial maintenance. The main problems are information unavailability, information sharing, communication, and information integrity. The SHELO model was developed as a framework for analyzing maintenance. It allows categorizing identified problems to work out solutions to them. The SHELO model takes interactions also without human influence into account. The SHELO model has been used successfully to analyze individual assets in industrial maintenance. In this paper, the SHELO model is used to analyze maintenance problems in a fleet.

Companies have usually a view only to the fleet of assets they own. However, a manufacturer or an equipment provider has knowledge of their products but the data and information is partly fragmented to the customers who have purchased the assets. Therefore the equipment provider has rarely access to all data of the fleet of assets that they have produced. Instead of just considering assets as a singular objects, considering them as a fleet can generate certain benefits, such as fault detection, resource optimization, and product or service development [4, 5]. Although the benefits have been somehow acknowledged, there are issues that hinder the exploitation of fleet-wide data. The challenges are mostly related to the availability of the data. The data is not shared smoothly between companies, but there might be challenges in transferring the data inside a single company as well. In order to utilize the fleet data to fleet management purposes, the challenges related to data sharing need to be identified and solved.

## II. BARRIERS AND BENEFITS OF SHARING DATA

The basic hypothesis of open data is that more intensive and creative use of data can generate new value. The information is understood as given, used uncritically, and trusted without verification. However, open data could be collected or created for other purposes. Open data has potential value, but also risks for validity, relevance, and trust. Open data is context- and time-dependent. Taken out of context, open data loses meaning, relevance and usability. Data collection, management, access, and dissemination practises have an effect on the quality of data. Data quality is often used to mean accuracy, but information quality is a much wider concept. [6]

Janssen [7] have identified a great number of benefits of open data. They cluster the benefits in (1) political and social, (2) economic, and (3) operational and technical benefits. Political and social benefits have been merged because they are difficult to separate. E.g. the following benefits are recognized as political and social benefits: transparency, more participation, creation of trust, access to data, new services, and stimulation of knowledge development. Economic benefits are economic growth, stimulation of competitiveness, new innovations, improvement of processes/products/services, new products and services, availability of information, and creation of adding value to the economy. Operational and technical benefits are reuse of data, creation of new data by combining data, validation of data, sustainability of data, and access to external problem-solving capacity.

Barriers to open data have been identified at the institutional level, in the task complexity of handling the data, the use of open data, participation in the open-data process, legislation and information quality, as well as at the technical level.

### *Institutional barriers are:*

- unclear values (transparency vs. privacy),
- no policy for publicizing data,
- no resources, and
- no process for dealing with user input.

### *Task complexity includes:*

- lack of understanding of the potential of data,
- no access to original data,
- no explanation of the meaning of data,
- information quality,
- duplication of data,
- no index on data,
- complex data format and dataset, and
- no tools for support.

### *Barriers in use and participation are:*

- no time,
- fees for the data,
- registration to download data,

- unexpected costs, and
- lack of knowledge to handle data.

### *Legislation barriers are:*

- privacy,
- security,
- license and limitations to using data, and
- agreements.

### *Information problems are:*

- lack of information,
- lack of accuracy of information,
- incomplete information,
- non-valid data,
- unclear value,
- too much information,
- information missing, and
- similar data stored in different systems yielding different results.

### *Technical barriers are:*

- data not in a well-defined format,
- absence of standards,
- no support,
- poor architecture of data,
- no standard software,
- fragmentation, and
- no systems for publicizing data. [7]

The barriers can be naturally grouped in different ways, e.g. Saygo and Pardo [8] define barriers according to four perspectives: (1) technological, (2) social, organizational, and economical, (3) legal and policy barriers, and (4) local context and specificity. Barry and Banister [9] divide the barriers to (1) economic, (2) technical, (3) cultural, (4) legal, (5) administrative, and (6) risk-related barriers.

More similar kinds of classification can be found in the literature under slightly different names. However, the list presented by Jansen [7] covers the topic extensively.

## III. RESEARCH DESIGN

The research methods used in this paper include seven interviews for data collection and qualitative means to analyze the interview data. As shown in Figure 1, the interview data was collected from 4 different departments of an original equipment manufacturer, and from 3 customer companies who use the product. These interviews were originally conducted to identify

and develop the offering of products and services. The secondary data answers were interesting, so the authors decided to analyze the answers with the SHELO model.

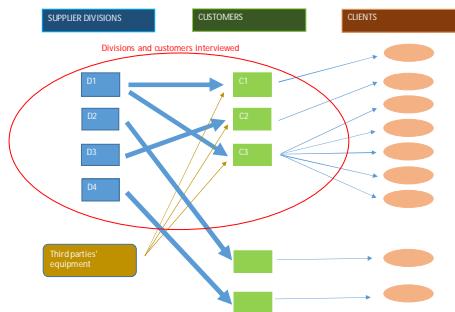


Fig. 1. Overview of the fleet of main products/services.

Customer 1 uses the products bought from division 1 to operate their own equipment. Customer 2 uses equipment and services from supplier division 3 to make their own products which are sold to a limited number of clients. Customer 3 has a lot of clients to whom they sell the products. All customers have also third parties' equipment, which makes the maintenance services much more challenging. The clients and third party suppliers were not interviewed. Divisions 2 and 4 sell products mainly to other customers than the ones that were interviewed.

The interviews were semi structured theme interviews. Only the divisions and customers inside the red oval shown in Figure 1 were interviewed. The answers were coded by using the SHELO model elements listed in Table 1. The data was thematically analyzed with NVivo version 10 software. The interviews and coding were done in Finnish, and the findings were translated to English.

Table 1. Content of SHELO model elements [3].

Element	Content
<b>S</b> - Software	Maintenance procedures Installation instructions Plans and schedules (Automated) algorithms of condition monitoring Regulations Warranty clauses
<b>H</b> - Hardware	Tools Materials Objects Equipment Computers, IoT, Data Buildings/ physical infrastructure
<b>E</b> - Environment	Environmental context Temperature Noise Economic environment
<b>L</b> - Liveware	Humans (operators, maintenance technicians, managers, designers, etc.) People interactions Personal attitude Skills and education Availability of personnel
<b>O</b> - Organization	Organizational structure

It should be noted that software and hardware do not mean the same in the SHELO model as in computer science. These terms are used because they were selected for the original SHEL model [10].

#### IV. FINDINGS – THE SHELO MODEL IN THE FLEET

Applying the SHELO model in the interview data showed that H, H-H, H-L, H-O, L-O, and O-O themes got the most hits in the codes. There were no codes in the elements S-S, S-I, and E-E. One explanation for this can be in the interview questions, which did not ask about instructions, procedures, plans, schedules etc. Another explanation is that the persons in the interviews were managers or directors, and they do not pay attention to these matters. If there had been e.g. mechanics in the interviews, these issues would have probably been considered. Codes to the categories are presented in table 2, e.g. code H means that it is clearly a tool-related issue. Code H-H means that it is related to both tools and materials, or there can be more than one party, e.g. a maintenance service provider and a material supplier.

TABLE I. THE SHELO DIMENSIONS AND NUMBER OF CODES FOR EACH CATEGORY.

S	H	E	L	O
S 5	S-S 0			
H 33	S-H 3	H-H 15		
E 2	S-E 1	H-E 5	E-E 0	
L 3	S-L 0	H-L 46	E-L 3	L-L 6
O 2	S-O 9	H-O 18	E-O 4	L-O 12
				O-O 21

Appendix A contains tables 3 – 19. The tables show the results that emerged when coding the interview answers to the SHELO model concepts. Tables 3 – 19 are in another file, which is linked to this document. The data is stored as a pdf file (a pdf reader is needed to open the data).

#### Appendix A

#### Findings in categories E, E-L, and E-O

Tables 3, 4 and 5 present environmental issues and possibilities. The most interesting matter in this part is the sharing economy and the companies' view that the technology is already mature enough. "Technology is available to collect big data but standards are missing." The sharing economy could be developed by adding transparency to data sharing and with other activities in a multi-company environment. "In the future transparency can be seen as **sharing economy**". The big question is how it can be implemented in a multi-company environment with a positive attitude." The regulations of maintenance and the missing of standards to share data were presented as barriers. "There are **barriers** for changing processes (e.g. in oil industry) because regulations specify the

*time between maintenance. And that's why health monitoring is not realistic to implement."*

The main **benefits or potential** of sharing data in categories E, E-L, and E-O are:

- technology
- transparency,
- support to decision making

The main **barriers** to sharing data in categories E, E-L, and E-O are:

- regulations
- missing standards

#### Findings in categories H, H-E, H-H, H-L, and H-O

Tables 6-10 present hardware (tools, materials, computers, data, etc.) -related codes. The most hits in codes are in these elements, which is natural because computers and data, as well as Internet of Things (IoT) belong to this part. The questions in the interviews were focused to this kind of topics. The management of big data was found to be a problem. "*The amount of process data is big, it can be used in something else than just process control.*" Also data from other systems is not accurate enough and it is difficult to use. "*Data from ERP is not accurate enough.*" The ownership of data was considered important, and when data sharing was needed it was done case by case. "*The ownership of data is important. The customer owns the data and wants to own it in the future.*" Clear rules to share data do not exist, so a time-consuming way to share data was used. The process to decide when to share data is not defined in companies. Despite the problems in sharing data, the advantages were understood: new business models, cost savings, the advantages of big data, remote control, better maintenance services, support to decision making, development of automation systems, and combined data from different systems. "*Better data management helps in decision making and in maintaining.*" Also clear fleet thinking was noticed: "*In health monitoring the decisions are made based on one equipment. There is potential to analyze the changes by comparing the whole group of the same kind of equipment.*" Even inside the same company there were problems in sharing data. "*Reports in the service business are not shared in divisions. Every division has its own reports, and service data is not easy to share.*" Also the basic idea of data sharing was missing: "*The barriers to share data are lack of knowledge and insufficient grounds of value added by sharing data. The win-win situation is not understood.*"

The main **benefits or potential** of sharing data in categories H, H-E, H-H, H-L, and H-O are:

- transparency enables new business
- IoT will help data sharing
- data sharing potential is known

The main **barriers** to share data in categories H, H-E, H-H, H-L, and H-O are:

- the ownership of data
- data quality
- technical problems in data collection
- defining which data is difficult to monitor
- data architecture
- the amount of big data
- data facilitator missing
- lack of knowledge, win-win not understood

#### **Findings in categories L, L-L, and L-O**

In tables 11 – 13 there are L findings, which are related to interaction between people or their attitudes and skills. Most of the findings concern developing a new way to do something. "At first systems and tools were sold as a product, but then IoT made it possible to sell them as a service. The demand increased a lot." "There is need to consider the value of service to the customer. Different data from divisions can be combined and new services can be offered." There are proposals to change something or to do something in a new way, and people may need new skills to use the new methods. E.g. in a fleet, comparing all ships together may give an interesting perspective to comparing maintenance data and details. "In the fleet the customer wants to compare all ships. Of course there is a challenge when the ships are of different ages. With new ships it is possible to compare different details between the ships." "To compare many customers' ships is interesting. Especially operation data and maintenance data are interesting things."

The main **benefits or potential** of sharing data in categories L, L-L, and L-O are:

- IoT makes it possible to sell better services
- combining data from different systems
- big data makes it possible to compare the customer's equipment at the same time (fleet)

The main **barriers** to sharing data in categories L, L-L, and L-O are:

- limitation of ERP systems
- rules are not clear in the offerings
- co-operation with other division is difficult when the work load is heavy
- big data is shared with divisions only case by case

#### **Findings in categories O, and O-O**

Organizational findings are presented in tables 14 and 15. The main findings are related to sharing economy, risk and revenue sharing, new ecosystems, and new earning models. "*In the future open data can be seen as a 'sharing economy', which will have a positive effect on the relationships between companies and service networks.*" The findings can create new business models if they can be implemented in business. Data sharing can be developed, and it will help improve the whole fleet actions, or at least help service providers create new services to the fleet e.g. in the decision support process and data analysis. "*It is important to understand that the whole network influences the customer, not only the actions of the first or last company in the network.*" "*Clients want both support for decision making and data analysis to be used in decision making.*"

The main **benefits or potential** of sharing data in categories O, and O-O are:

- discussion with clients is possible at many levels
- clients want support for decision making and data analysis, which can be done only by sharing data

The main **barriers** to sharing data in categories O, and O-O are:

- support to handle third parties' equipment is missing
- the process of contacting the "right person" is not working
- clients want to invest once but are not willing to pay for monthly services

#### **Findings in categories S, S-E, S-H, and S-O**

The findings presented in tables 16 – 19 related to procedures, instructions, regulations, etc. did not have many hits in codes because people in the interviews were at a high level in hierarchy. "*The regulations will be tighter and more accurate than now, and that will set up new demands for data collection and presentation of data.*" An interesting finding was that those companies that shared emission data openly were willing to accept tighter and more accurate regulations in emission. Their products are probably more eco-friendly than those of others. "*The clients in this business are interested in environmental issues. Some clients are ready to open data, and more openness is wanted.*" Another interesting finding was that in the interviewed companies it was understood that new business models need new kinds of responsibility. New business is based on data sharing and new services, which need attention to collaboration and trust in business partners. "*Rules must have been agreed on with partners beforehand.*"

The main **benefits or potential** of sharing data in categories S, S-E, S-H and S-O are:

- eco-friendly solutions
- new business models can be created

The main **barriers** to sharing data in categories S, S-E, S-H and S-O are:

- it is challenging to optimize a large fleet instead of one asset
- regulations and laws are unclear/local
- suspicion that someone will understand the data better and use it for their own purposes when data is openly shared

## V. CONCLUSIONS AND FUTURE WORK

This paper shows that the SHELO model could be used to analyze the problems in data and information management, as well as data sharing problems in asset management at the fleet level. The identified problems could be categorized for further analysis to classified problem areas and for identifying solutions. Problems in information management could be identified by analyzing the interview data with categories contained in the SHELO model.

Data sharing has a good potential in fleet management. Clients want both support for decision making and data analysis to be used in decision making. E.g. a fault situation causes a lot of problems for the company and its clients. It would be beneficial to know beforehand when the equipment could have problems, so that the client could be informed. The results of the study showed that data is shared with the maintenance staff but not with the customer, and also combinations of data from different data sources are not used properly. Better data management would help in decision making and maintaining. Customers will give out data when the services are important to them. However, there are barriers to data sharing:

- Lack of knowledge and insufficient ground of value added by sharing data. The win-win situation in fleet management is not understood.
- Data is shared only case by case when needed.
- Every division has its own reports and service data is not easy to share.
- Data contains confidential information which it is not allowed to share.

Now data is shared and combined only case by case when needed. The ownership of data is important. The customer owns the data and wants to own it in the future. Complexity is growing and it is difficult to notice important data automatically in the very large amount of collected data. Rules to sharing and combining data are missing even though the advantages of data sharing can be seen.

In the future, open data can be seen as a “sharing economy” which will work positively between companies and fleet service networks. Transparency in data sharing will enable new business models. New ecosystems are spoken of but when creating a new ecosystem, there is a need for a lot of dialog with different parties. New models can be based on data sharing, and that is why more responsibility is needed. If “risk and revenue sharing” is the target, also the supplier needs to give more and take more risks and responsibility in order to co-operate. Customers are

more interested in environmental issues than before. Some customers are ready for open data, and more openness is wanted.

The maintenance playground is fragmented, it has a large number of actors, and they have their own systems which do not work together. The different systems hinder companies' possibilities and motivation to define a common platform. So far there is no evidence that a common platform could be implemented in the near future. Transferring into platform-based business where data sharing is of major importance would be a fundamental change for many industrial companies operating with traditional business models. Most companies have been cautious in adopting practices that would take them towards a common, inter-organizational platform. However, the real value of fleet management lies in integrating and analyzing data of various assets, although comparing assets of different ages is not always straightforward. In contract business there is also third parties' equipment, and this equipment needs a support network. On the network level, standardized ways of action are needed. A new research area would be to coordinate subcontractors and clients to create a new solution or a pilot to define new rules to sharing data.

A limitation of this research was that only divisions and some of their main customers were interviewed. This was because the interviewed parties had a part in a fleet project.

Future research is needed to widen the investigation to find out what clients and third party equipment suppliers need to be able to share data or use shared data. More research is needed to investigate the root causes to solve the problems found in this research and to create new methods to develop collaboration and data sharing rules in fleets.

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## Appendix A

Identifying the sharing needs, problems and benefits of fleet data with the Shelo model

Lasse Metso, Salla Marttonen-Arola, Maaren Ali-Marttila, Sini-Kaisu Kinnunen, Timo Kärri

Lappeenranta University of Technology

LUT School of Business and Management

The elements of the SHELO model are (shown in Table 1):

- S Software: Maintenance procedures, Installation instructions, Plans and schedules , Automated algorithms of condition monitoring, Regulations, Warranty clauses
- H Hardware: Tools, Materials, Objects, Equipment, Computers, Internet of Things (IoT) Data building/ Physical infrastructure
- E Environment: Environmental context, Temperature, Noise, Economic environment
- L Liveware: Humans (operators, maintenance technicians, managers, designers, etc.), People interactions, Personal attitude, Skills and education, Availability of personnel
- O Organisation: Organisational structure

Codes C1, C2, C3, D1, D2, D3 and D4 used in the tables below are shown in figure1. D stand for the divisions and C for the customers interviewed.

The following tables 3 – 19 show the results that emerged when coding the interview answers to SHELO model concepts.

*Table 3. E findings.*

E
The electrical network is a main issue in maintenance. If there is no electricity, there is no action. C1
Need for international standardisation in protective relay. C1

*Table 1. E-L findings.*

E-L
The division has a lot of substance know-how and industry-specific selection of products which offer added value to customers. D2
Service orientation is essential to fulfil customers' needs. Complex services be developed with IoT. D2
There is a need for studying the customer value of services. There is a need to make better services together with other divisions. D2

*Table 2. E-O findings.*

E-O
The revolution of industry was seen as a risk in business. Product 1 sells well but product 2 not so well. Maintenance in product line 1 is at maximal level (usability). In product line 2 more risks can be taken in maintenance. C1

In the future, transparency can be seen as "sharing economy". The big question is how it can be implemented in a multi-company environment with a positive attitude. C2
There are barriers for changing processes (e.g. in oil industry) because regulations specify the time between maintenance actions. That is why it is not realistic to implement health monitoring. D2
The technology is available to collect big data but standards are missing. D2

Table 3. H findings.

H
Data from the process is of good quality, and possible problems arise usually with data produced by measuring equipment. C1
The amount of process data is big, and it can be used in something else than just process control. C1
There is enough data but the problem is that the data from ERP is not accurate enough. There can be errors in feeding information to the computer and exploiting it can be difficult. C1
The potential of big data potential is interesting, as well as knowing the risks. C1
Interruptions in production or minor errors cost different amounts, so it is difficult to calculate the potential of savings. C1
The ownership of data is important. The client owns the data and wants to own it in the future. C1
Sensors as the way of measurements are considered in order to find out new services in the future. Today there are phenomena which are impossible to measure with the present sensor, but there is potential to create something new based on this in the future. C2
CBM enables performing maintenance when the machines are not used, so it saves costs because extra stops are not needed. C2
It is difficult to evaluate how much of the improvement can be calculated to ICT / IoT and process developing when they are done concurrently. C2
IoT solutions should made for critical equipment because there is most potential for development. C2
Complexity is growing and it is difficult to notice important data automatically from very large amount of collected data. C2
The problem in IoT is to create a model in which data can be analysed and give right instructions as well as guide human actions to the right direction. C2
Transparency in data sharing enables new business models. C2
The more aware the client is, the more data he/she will demand. The rights of the data user need to be defined. C2
"Our data, our equipment". C2
Big data and ICT possibilities are only partly known, but how can advantage from big data be taken, is the question. The amount of big data is huge and it is used on quite a low level. The target is to prevent failure situations by doing wise data management. C3
Faulty connections must be found quickly to help the operator and assembler in maintenance. C3
Maintenance has been time-based but now it is wanted to be changed to condition-based. If the system tells what needs to be done and in which order, this can prevent extra work and save costs. C3
The service plan is based on existing technology and know-how. The business view is essential when developing new service products, production is more important than one client's need. D1
Our services are connected to installed equipment. The focus is on maximizing the life time of equipment. D1
Service developing is continuing improvements and iteration. D1
The distance to the client makes services difficult to manage. D1
Service descriptions help manage services. Service descriptions should not be work instructions but general level descriptions. D1
Remote control is in focus to get enough data to offer services to clients. D1
It is a problem that there is no data available of maintenance actions made in the past and what the condition of the equipment is now. D1
Online data is not yet in use but measurement data can help recognize the need for maintenance, and as

well as point out the benefits of maintenance services. D1
When service contracts are based on the condition and in next step on data, then right services are available at the right time. D1
In data-based maintenance predictable and price models are challenges. Costs should be minimized but remote control costs a lot. D1
Defining monitoring data is difficult. D1
Putting data to a database should happen only once and the data should also be pre-selected in order to minimize mistakes. D1
Is there untapped potential available? They can be noticed by using databases. D1
New services have been developed: remote support and control, condition monitoring, health check, life cycle assessment. D4
A lot of technical solutions exist, but the architecture of the data and the service portfolio are difficult to solve. D4

Table 4. H-E findings.

H - E
Process data is not collected by relays. C1
Health data of relays is collected and used. C1
In health monitoring the decisions are made based on one equipment. There is potential to analyse the changes comparing the whole group of same kind of equipment. C1
How about intelligence relays? The data collection could be done by separate equipment, not by relay. C1
It must be possible to integrate the new solutions with all the manufacturer's equipment. C2

Table 5. H-H findings.

H - H
Relays do not collect data from equipment, they protect. Only faults are monitored online. C1
It is not known what data it is possible to collect from new relays. The data when the relay needs maintenance and fault history are needed. C1
There is no link between maintenance databases and automation systems. C1
History data is now used only for troubleshooting, but there is potential to forecast the need of maintenance and to use databases better, as well as to use life-cycle data. C1
Better data management helps in decision making and maintaining. C1
Health monitoring and measurement data are not used enough. Faults could be minimized by improving this. C1
Developing processes and automation systems can be seen as a possibility to develop data management. Now data is collected time-based online. C1
Different data in different databases are seen as a challenge or as a barrier. In the future the target is to use the data better than it is done at the moment. C1
Faults caused by relays are not recorded, more faults are caused by breakdowns in the power-distribution network. C1
Data is formatted "badly", it is on paper or difficult to automate in some other way. Manual data is difficult to use. D1
It is difficult to define which data to collect. D1
Integrated systems record data but not enough. It is impossible to see trends from insufficient data. D1
The amount of data can be very big. Only KPI data is analysed and the whole data is checked if needed when problems are noticed. D2
Integration is a challenge. How can all needed data be collected through one cable and then used? D3
Data transmission connection is used. The supplier monitors the equipment delivered to the customer. When the supplier noticed a fault in the equipment it is possible to inform the customer about this fault

and give instructions for how to deal with it. D2

*Table 6. H-L findings.*

H – L
The biggest problem is the quality of the data in ERP systems because people can make mistakes when inputting data. C1
Faults are not recorded statistically, but the staff notices when equipment has broken more often than before. C1
The company has strategic-level support decision tools, but it expects that the service provider will offer tools for the operational level. C3
Relays have been "stupid" before but now real-time data is much more available. Relays should be used much more. C3
Data analysis and decision support are needed, as well as traffic lights to observations from data. C3
The company collects data and understands what is needed. The supplier should have connections to analyse data and give support for decision making. C3
A lot of data is available but the company does not want to give the role of the data manager to anyone else, even though support is needed to analyse big data. C3
Fault situations cause a lot of problems to the company and the company's clients. It would be better to know beforehand when the equipment might have problems, so that the client could be informed. C3
Relays are quite reliable but more analysis is needed for wider fault management in the network – what can the relay tell about the whole environment? C3
There is need to discuss not only relays but the whole automation system. C3
It is urgent to locate the faulty equipment and what exactly is broken. C3
In the underground cable network the relay could discover changes in the cable. C3
Relays could create data for maintenance staff, e.g. work order. C3
More automation – decision support proposals to the maintenance staff. C3
Customer needs are important but not all wishes can be fulfilled. Technical skills and own knowledge can limit this. D1
Data sharing has good potential. Now data is shared with the maintenance staff but not with the customer, and also combinations of data from different data sources are not properly used. D1
Online data is not available but it can be organised in an emergency. D1
Online data would offer other information but the customer does not have online data systems. D1
If fault data is available, it can be used to offer better services even when no errors occur, as well as new products to customers. D1
A wider perspective with different equipment. Is it possible to use only one database or are more databases needed? Is the combined database information too general and are there enough details? Is the information useful still? D1
How can the supplier be seen united from the customer perspective? Service based on data is challenging. The united system should be created step by step and internal services should be defined first. D1
There is potential to use better data created by equipment, at least in locating errors and doing maintenance actions faster. D1
From the customer point of view, the supplier services look different than from the supplier's view. The solution is a standardized service process. D1
Standardization of products helps also in the phase of call for bids and it standardizes offers for sale. D1
One department has know-how to model networks, but that is not put to use in maintenance. D2
IoT enables doing things more effectively, and more complex tasks can be done. Changes in the service concept and new services are needed. D2
Software and services to the core business of the customer are available. D2
The customer must realise the value of sharing data. The supplier does not want to get data in its own cloud computing, but services to data can be organised in customer servers. D2

There is potential to combine online data with process data, visualize data, store data, combine relevant data and define what is essential. D2
IoT enables better services to customers and makes remote control possible. D2
The demo environment makes it possible to simulate many different situations which are not possible in a real environment. D2
The suppliers' product groups have different variations and it is difficult to offer the same services to all the products the customer has bought. D3
Data is collected, and support to optimize the energy consumption is given. Also remote support, fault diagnosis, and health monitoring are possible because the equipment is "intelligent". D3
It is a challenge to sell data-based services because customers are used to getting also maintenance staff at the same time. D3
It is easy to share data which is collected by equipment, also analysis and reports to the customer are quite normal actions. The challenge is influencing the customer's decision making with the analysed data. D3
Data is used to find out what has been broken but there is need to prevent breakdowns by predicting. D3
Predictability is interesting to the customer because they can do maintenance actions when it is possible to do them in the right time. D3
Customers give data when the services are important to them. D3
Fleet data gives potential to process optimisation, energy optimisation and coping with quality problems. D3
Lack of technical data makes responses to the customer slow. D3
A demand for a monopoly of data is a challenge. The customer does not understand the potential of new services based on data sharing. D3
IoT gives more possibilities to offer new services to the customer even when they buy only products. D3
Divisions share their own data quite openly with other divisions because it has been understood that this helps to develop new products and services. D3
Some customers do not want to give the location of the equipment and health data. Also cloud computing is denied. D3
The barriers to sharing data are lack of knowledge and insufficient ground of value added by sharing data. The win-win situation is not understood. D3
Customers are not willing to share data because they think that the supplier will want to make the maintenance their own business. D3

Table 7. H-O findings.

H - O
Relay life cycle only 5-10 years, not worth collecting data. C1
The client owns the data and wants to own it in the future. C1
Intelligent relays may add value, but client does not want to pay more than now. C1
Health monitoring data and operation time data could be given to a selected partner. Data supports planning services better. C1
Health monitoring data could be analysed better by the supplier than what could be done in-house. Analysis service is not used now. C1
Data could be shared case by case. Production quality and product recipe data are not allowed to be shared. C1
With strategic partners data could be shared more in order to do better analysis. C1
IoT offers possibilities to optimize. How can we offer new services to our client to increase efficiency? C2
Can IoT generate new business? Are the clients satisfied with the results? C2
An aware client will need more data. C2
Who owns the data? C2

The data contains also customers' identification data and it is not allowed to share that. Other data can be shared if the advantages of sharing are clear as crystal. C3
In service business there is a common problem with a lot of "working hands". So there is a lot of variables. Product management is easier. D1
The customer is not an expert of the equipment, and they are only interested in the equipment when the devices do not work. D1
Support to the customer is given in planning maintenance and maximising the life cycle. Customers are not ready to invest in new products. D1
Is the data analysis done in order to develop the supplier's own business and processes or to create added value to customers? D1
Reports in service business are not shared in divisions. Every division has its own reports, and service data is not easy to share. D3
Remote service has developed extremely well. D4

Table 8. L findings.

L
At first systems and tools were sold as a product, but then IoT made it possible to sell them as a service. The demand increased a lot. D2
There is need to consider the value of service to the customer. Different data from divisions can be combined and new services can be offered. D2
In the spare part database, only the own country can be seen, but the division has spare parts in many countries, and the balance of those spare parts cannot be seen. D3

Table 9. L-L findings.

L - L
There is need to get suitable skills to be used in fault situations. D1
There are service contracts which include offerings of different divisions. Developing tools is an issue. ERP systems do not support this. D1
Clear rules for supplying know-how in common offerings. D1
Training is needed when business is transferred to data-based services. D1
Common offerings with other divisions are difficult when the work load is heavy. D1
The model of working is changing, which can be seen as a good thing and as a sign of development. D4

Table 10. L-O findings.

L - O
The client view is sometimes missing. If data collection and operations with critical components are in order, the other equipment maintenance can be organised as time-based. C2
Information is not used to plan marketing. "The data is this and it shows that a sales person is needed to visit the client". C2
A sales person need tools based on data to find out the client's need. C2
An example: "At first we sold systems and tools as products. Then we offered tools as a service and the demand increased a lot when we learned to offer our own know-how and tools as a service." D2
Predictability interests the customer because they can schedule maintenance actions when the ship is in the harbour. D2
Service data reports are not transferred to other divisions. Every division has their own reports and documents and it is a challenge to transfer the service data reports. D3
There is available data and service to the customer on how to operate the equipment, but the customer decides how to use the data. Also analysis and data visualization services are available. D3

Automation could be added and even replace humans in condition monitoring because humans make errors. With data and sophisticated mathematics this could be done better than humans can do. D3
Big data is not shared with divisions, but the advantages of sharing data is obvious. Now data is shared and combined only case by case when needed. D3
In motors different components can be compared with the customer's fleet. D3
In the fleet the customer wants to compare all ships. Of course there is a challenge when the ships are of different ages. With new ships it is possible to compare different details between the ships. D3
To compare many customers' ships is interesting. Especially operation data and maintenance data are interesting things. D3

Table 11. O findings.

O
In asset management strategy the target is to maximize the life cycle of the equipment and to get as much as possible profit with it. C1
It is urgent to create and develop ways to support third parties' actions and to charge for those services. C2

Table 12. O-O findings.

O – O
Special know-how is bought from outside the company when own knowledge is not enough or there is not enough resources available in the own company. C1
We do not have a contract of maintenance with the supplier but material and technical support is bought when needed. C1
Co-operation with the supplier of the equipment is smooth, and data collected by the supplier is tried to be used e.g. to find out what the equipment life cycle is. C1
Discussions with clients take place at many levels. In the supplier's view it is important to get right information to right people in the whole fleet at the same time. C2
When dealing with a maintenance contract to a whole power plant, it is important to build support for third parties' equipment and services. C2
At the moment people know somebody who to contact if problems appear. For example, it is impossible to find the right contact with the subcontractor. There is a lot of potential to consolidate the processes. C2
The client informs the subcontractor directly, the supplier does not know anything, and everything is mixed up. C2
In the future open data can be seen as a "sharing economy", which will have a positive effect on the relationships between companies and service networks. C2
It is important to understand that the whole network influences the customer, not only the actions of the first or last company in the network. C2
Solutions must be developed with the possibility to integrate them to other systems (customers' or other suppliers' platforms). Integration and openness must be considered. C2
The maintenance playground is fragmented and it has hundreds of doers who have their own systems which do not work together. It is impossible to define a common platform. There is no evidence that a common platform will appear. C2
When you analyse data and you need more data from other sources, you need to convince the other parties about getting added value for giving the data. C2
New ecosystems are spoken of, but when creating a new ecosystem, a lot of dialog with different parties is needed. C2
There is not much discussion on what the client demands and needs are. Divisions develop products and solutions separately. C2
It would be ideal if the coordinator could get the subcontractors and clients together to create a new solution or a pilot. C2

New models need more responsibility. If "risk and revenue sharing" is the target, also the supplier needs to give more and take more risk and responsibility in order to get the client to come in. C2
The supplier cannot lock itself to the business model in use. Some clients want to try new models and some want to change the action only when forced. The ability to offer services to different environments is needed. C2
The supplier wants to sell a product, while the client wants to get solutions. The client has bought products and solutions from many companies, and more effective integration is needed. C2
Clients want both support for decision making and data analysis to be used in decision making. C2
The clients expect sophisticated solutions found in the world which are not yet used in Finland. C2
Customers are used to investing a lot of money once but they are not familiar with monthly payments for services. D1

Table 13. S findings.

S
The regulations and laws are unclear. Is continuous measurement of emissions needed in the marine? C2
Regulations in the marine are local. Global emission measurement is not used as widely as local. e.g. on the Baltic sea. C2
The regulations will be tighter and more accurate than now, and that will set up new demands for data collection and presentation of data. C2
The supplier has more eco-friendly solutions than others, and from their point of view tighter regulations are not a bad thing. C2
Rules must have been agreed on with partners beforehand. C2

Table 14. S-E findings.

S - E
Preparations for massive faults in the power distribution network must be organised because the regulations require it. C3

Table 15. S-H findings.

S - H
It is a challenge to optimize 60 ships instead of one ship. How can we optimize the whole fleet? Some solutions are available, but tools to optimize the whole fleet are not available. C2
As a part of sustainable development quality, recycling and eco-friendly working make it possible to develop new sources of energy. C3
The processes and practices are changing. Especially when trying to achieve big advantages, the processes could be caught in a circle of change. D2

Table 16. S-O findings.

S - O
The clients in this business are interested in environmental issues. Some clients are ready to open data, and more openness is wanted. C2
In contract business there is also third parties' equipment, and this equipment needs a support network. On the network level, standardised ways of action are needed. C2
One common platform is not realistic, because companies have different systems. C2
Optimistically, if there is no direct competition between the parties, it is possible to open data and find out new opportunities. C2
Creating new ecosystems needs a new view to look at co-operation and a lot of dialog between the

parties. C2

Many doers are afraid that someone else will have more understanding, and that will prevent the sharing of data. C2

Finding an outside facilitator whom everyone trusts could be challenging. Maybe the client can take the role and manage the whole. C2

Covering data and not sharing it can cause a situation where an outside doer takes charge of the whole business, doing it in a new way and possibly without using the covered data. C2

New models mean more responsibility. C2



## **Publication IV**

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**AN ECOSYSTEM PERSPECTIVE ON ASSET MANAGEMENT INFORMATION**

Lasse METSO  
*Lappeenranta University of Technology*  
Mirka KANS  
*Linnaeus University, Växjö*

**Abstract:**

Big Data and Internet of Things will increase the amount of data on asset management exceedingly. Data sharing with an increased number of partners in the area of asset management is important when developing business opportunities and new ecosystems. An asset management ecosystem is a complex set of relationships between parties taking part in asset management actions. In this paper, the current barriers and benefits of data sharing are identified based on the results of an interview study. The main benefits are transparency, access to data and reuse of data. New services can be created by taking advantage of data sharing. The main barriers to sharing data are an unclear view of the data sharing process and difficulties to recognize the benefits of data sharing. For overcoming the barriers in data sharing, this paper applies the ecosystem perspective on asset management information. The approach is explained by using the Swedish railway industry as an example.

**Key words:** open data, data sharing, information management, information model, business ecosystem, asset as a service

**INTRODUCTION**

Open data sources, for instance in the form of Big Data (BD) and the Internet of Things (IoT) have changed the business models in several ways. The increased number of partners involved in value creation, and access to a large amount of data allows for more complex business models and collaboration patterns. Rong et al. [1] claim that IoT is more than a support for the supply network; IoT should be understood as a business ecosystem. They also note that there is very limited research in IoT ecosystems. Thus, there is a need to understand the new business patterns and map the information requirements within business ecosystems. One attempt to model the influences of big data on different actors in the business ecology dynamically is found in [2]. Asset Management (AM) is a domain in which BD and IoT bring great opportunities, but also great challenges, for instance as regards the sharing of data. Open data can create new value by intensive and creative use of data, for instance resulting in the optimization of maintenance and operations, and prolonged asset lifetime. The service provider can for example give support for decision making by collecting data from several plants and identifying similarities in the data, and create new and better analysis based on the combined data.

One of the challenges is that a lot of open data appears in situations and activities that are different in context and time of its definitive use. When data is taken out of context, it loses its meaning. Operational data is usually defined at the point of creation in just enough detail to support the people who operate the system or use the data directly. According to [3], data collection, management, access, and

dissemination practices have a strong effect on the extent to which datasets are valid, sufficient, or appropriate for further use. Data quality is generally understood in terms of accuracy, but studies have identified multiple aspects of information; quality is more than just accuracy of the data [4]. In [5] data quality is described as data fit for use by data consumers, including dimensions of accuracy, consistency and security, as well as relevancy and understandability.

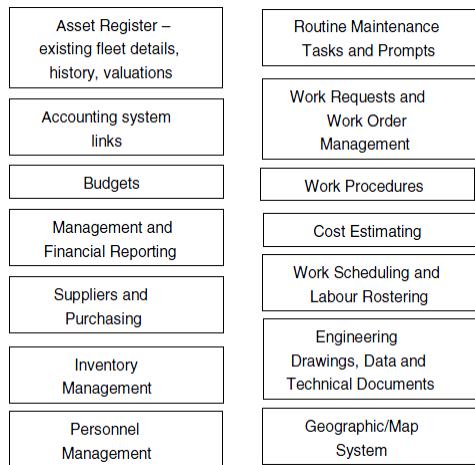
Applying the ecosystem perspective in asset management is a way to overcome some of the challenges in information sharing. The purpose of this paper is to address the barriers for data sharing within AM by suggesting an ecosystem solution. First, an understanding of the barriers and opportunities for data sharing is created by using an empirical approach. Thereafter, a conceptual solution is suggested with support from contemporary ecosystems research. The paper is organized as follows: in the next section the relevant background regarding asset management is given. Next, the concept of data and information sharing is introduced, and the results of an empirical study of opportunities and barriers for information sharing within AM are presented. Thereafter, the ecosystem approach is utilized for conceptual modeling of a solution to the barriers for information sharing in AM. Finally, concluding remarks are given.

**ASSET MANAGEMENT AND ITS INFORMATION NEEDS**

Assets are entities that bring potential or actual value to an organization [6]. The value varies with the context, organization and situation, and could be tangible or intangible, as well as financial or non-financial. Asset management can

be described as a set of activities for reaching a given business or organizational objective [7], including identifying the required assets and funding, acquiring the assets, providing logistics and maintenance support, and disposing or renewing the assets.

An organization defines the internal and external communications relevant with respect to the assets, asset management and asset management system: what, when, to whom, and how to communicate [8]. An asset management information system is designed to create and maintain documentation of asset management functions [7]. Asset management information systems are used to identify equipment, locations and activities. These systems are also known as Computerized Maintenance Management Systems (CMMS). Figure 1 shows the main applications of asset management information systems, which correspond with the information requirements for an asset [9].



**Fig. 1 Asset management information system**

Source: [7].

The data requirements are different between fixed and mobile equipment. The main difference is location. In mobile equipment, Global Positioning Systems (GPS) and maps are probably needed [7]. The organization has to take into consideration the risks, roles and responsibilities, as well as the processes, procedures and activities in asset management, information exchange, and the quality and availability of information in the decision making processes [8]. Information in asset management activities is listed under the relevant subject areas: data management, condition monitoring, risk management, quality management, environmental management, etc. [10]. The organization determines the attribute requirements and the quality requirements of information, and how and when the information is to be collected, analyzed and evaluated [8].

#### OPEN DATA ACCESS

Open Data was originally a concept in which governmental data were available to anyone with a possibility of redistribution in any form without any copyright restrictions [11]. Nowadays the definition of Open Data is wider: "Open data is data that can be freely used, shared and built-on by anyone, anywhere, for any purpose" [28]. A clear

and consistent understanding of what Open Data means is important if the benefits of openness are to be realized, and to avoid the risks of compatibility between projects [12]. All Open Data is publicly available, but not all publicly available data is open. Open Data does not mean that an organization releases all of its data to the public. Open Data means that data is released in a specific way to allow the public to access it. The focus is on what data is available and how the data is available. If Open Data is misread as releasing all data, privacy becomes an issue [13].

Data sharing has been recognized as a good behavior in science and technology research. Data sharing enables researchers to ask new questions based on shared data, as well as advance research and innovation [14, 15]. The medical community has found the benefits of data sharing [16, 17], such as the system of open access that was released to the pharmaceutical industry by GlaxoSmithKline in May 2013. The system contains patient-level data from clinical trials of approved drugs and failed investigational compounds. An independent panel decided which data was available to responsible users. Jansen et al. [18] classify the benefits of open data into political and social, economic, and operational and technical benefits. Political and social benefits include for example transparency, more participation, creation of trust, access to data, new services, and stimulation of knowledge development. Economic benefits are economic growth, stimulation of competitiveness, new innovations, improvement of processes/products/services, new products and services, availability of information, and creation of adding value to the economy. Examples of operational and technical benefits are reuse of data, creation of new data by combining data, validation of data, sustainability of data, and access to external problem-solving capacity.

In [18] the barriers to Open Data are identified as follows:

- institutional level barriers,
- task complexity of handling the data,
- the use of open data and participation in the open data process,
- legislation,
- information quality, and
- technical level barriers.

Institutional barriers are: unclear values (transparency vs. privacy), no policy for publicizing data, no resources, and no process for dealing with user input. Task complexity includes lack of understanding the potential of data, no access to original data, no explanation of the meaning of data, information quality, duplication of data, no index on data, the data format and dataset being complex, and no tools available to support. Barriers for the use of open data and participation are: no time, fees for the data, registration to download data, unexpected costs, and lack of knowledge to handle data. Legislation barriers are: privacy, security, licenses and limitations to use data, and agreements. Information problems are: lack of information, lack of accuracy of information, incomplete information, non-valid data, unclear value, too much information, missing information, and similar data stored in different systems yields different results. Technical barriers are: the data is not in well-defined format, absence of standards, no support, poor architecture of data, no standard software, fragmentation, and no systems to publicizing data.

Other ways to group the barriers also exist. For instance Saygo and Pardo [19] define the barriers from four perspectives:

- technological barriers,
- social, organizational, and economical barriers,
- legal and policy barriers,
- local context and specificity.

#### **EMPIRICAL STUDY ON PRACTITIONERS' VIEW**

In this section, the results of an empirical study of the barriers and benefits of shared information for asset management are presented. The study included seven interviews in total. The interview data was collected from managers and directors of four different departments at a Finnish Original Equipment Manufacturer (OEM), and from managers and directors of companies who purchase those products. Theme interviews were used, and the answers were coded with NVivo. The interviews and coding took place in Finnish, and the main findings were translated into English. The findings were classified according to the barriers and benefits to open data presented in [18]. The barriers were classified to the institutional level, the task complexity of handling the data, the use of open data and participation in the open data process, legislation, information quality, and technical level barriers. The benefits were classified to political and social, economic, and operational and technical benefits.

##### *Barriers for data sharing*

###### **1. The institutional level barriers**

The ownership of data is important. The customer owns data and wants to own it in the future: "Our equipment, our data". For example, customers do not want to reveal the location of equipment and health data. Data containing the customer's identification are not allowed to be shared. The same goes for production quality data and product recipe data. Other data can be shared if the advantages of sharing are clear. There is a prejudice against cloud computing in companies. A lot of data is available, but companies do not want to give the role of the data manager to anyone else, even though support is needed to analyze big data. The customer does not share data because they think that the supplier wants to take the maintenance to its own business. The demand for the monopoly of data is a challenge. The maintenance playground is fragmented and it has hundreds of doers, who have their own systems which do not work together. It is impossible to define a common platform, and there is no evidence that a common platform would appear. For data-driven maintenance, predictability and pricing models are challenges. The cost should be minimized, but remote control costs a lot. It is a challenge to sell data-based service because the customers are used to getting also maintenance staff at the same time.

###### **2. Task complexity in handling the data barriers**

The complexity in data management is growing, and it is difficult to notice important data automatically in a very large amount of collected data. Different data in different databases are seen as a challenge or as a barrier. In the future, the target is to use data better than today. The amount of process data is big, and it can be used for something else than just process control. Defining the monitoring of data is difficult. Process data is not collected by equipment, but health data is collected and used. There is no link between maintenance databases and automation systems.

Putting data into a database should happen only once, and the data should also be pre-selected in order to minimize mistakes. It is a problem that there is no data available of maintenance actions made in the past and about the condition of the equipment now. It is not known what data it is possible to collect from new relays. The data when the relay needs maintenance and the fault history are needed. The customer's needs are important, but not all wishes can be fulfilled. Technical skills and own knowledge can limit the offering of new services to the customer.

###### **3. Barriers for the use of open data and participation in open-data process**

The barriers to sharing data are lack of knowledge and insufficient grounds of value added for sharing data. The win-win situation is not understood. Many doers are afraid that someone else will have better understanding, and this prevents the sharing of data. Online data is not available but it can be organized in an emergency. Online data would offer other information, but customers do not have online data systems. Big data is not shared between divisions, although the advantages of sharing data are obvious. Now data is shared and combined only case by case when needed. With strategic partners, data could be shared more to do better analysis. Data is shared with the maintenance staff but not with the customer, and also combinations of data from different data sources are not used properly.

###### **4. Legislation barriers**

There are barriers for changing the processes (e.g. in the oil industry) because regulations specify the periods between maintenance operations. That is why it is not realistic to implement health monitoring. The regulations and laws are unclear. Regulations in the marine are local. Global emission measurement are not used as widely as local e.g. in the Baltic Sea. One could therefore ask whether continuous emission measurements are needed or not in maritime industry. Regulations will be tighter and more accurate than now in the future, and that will set up new demands for data collection and the presentation of data. When a supplier has a more eco-friendly solutions than others, then from their point of view tighter regulations is not a bad thing.

###### **5. Information quality barriers**

There is enough data, but the problem is that the data from Enterprise Resource Planning (ERP) is not accurate enough. There can be errors in feeding information to the computer and exploiting of it can be difficult. The biggest problem is the quality of the data from ERP systems because people can make mistakes when inputting data. The data is formatted "badly", it is on paper, or somehow else difficult to automate. Manual data is difficult to use.

###### **6. Technical level barriers**

Technology is available to collect big data, but standards are missing. It is difficult to define which data to collect. Integrated systems record data but not enough. It is impossible to see trends from insufficient data. The amount of data can be very big. Only Key Performance Indicator (KPI) data is analyzed and the whole data is checked if needed when problems are noticed. Integration is a challenge: how can all the needed data be collected through one cable and then used?

##### *Benefits of information sharing*

###### **1. Political and social benefits**

In the future, open data can be described as a "sharing economy" which affects positively between companies and

service networks. Transparency in data sharing enables new business models. New ecosystems are spoken of, but when creating a new ecosystem a lot of dialog with different parties is needed. More responsibility is needed from both supplier and customer when implementing new models. If "risk and revenue sharing" is the target, also the supplier needs to give more and take more risk and responsibility in order to get the client come in.

#### 2. Economic benefits

There is need to consider the value of the service for the customer. Different data from the divisions can be combined and new services can be offered. The potential of big data is interesting, as well as knowing the risks. The service plan is based on existing technology and know-how. The business view is essential when developing new service products, and production is more important than one client's needs. Training is needed when business is transferred to data-based services.

#### 3. Operational and technical benefits

With more automation decision support proposals can be created to maintenance staff. The equipment could create data for the maintenance staff automatically, e.g. work orders. The clients want both support for decision making and data analysis to be used in decision making. Data is collected, and support to optimize energy consumption is given. Also remote support, fault diagnosis, health monitoring are possible because the equipment is "intelligent". The supplier cannot lock itself to the business model used. Some clients want to try new models and some want to change action only when forced. The ability to offer services for different environments is needed. Data analysis and decision support are needed, as well as traffic lights to observations of data.

#### 4. Potentials for data sharing

The more aware the client is, the more data they will demand. Data user rights need to be defined. Online data is not yet in use, but with measurements, the data can help to recognize the need for maintenance, as well as point out the benefits of maintenance services. The amount of big data is huge, but it is used at quite a low level. The target is to prevent failure situations by managing big data. Data can be transferred from clients also with remote control to create new services for them.

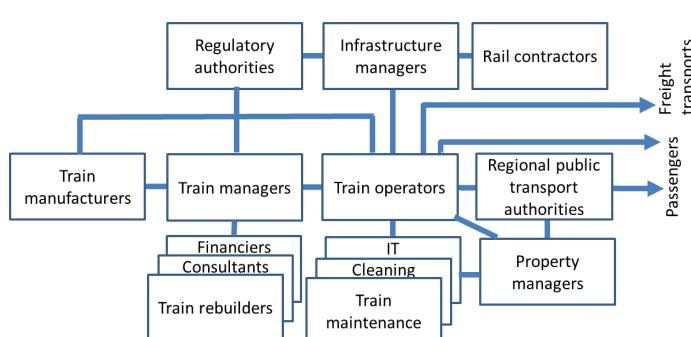
The client company collects data and understands what is needed. The supplier should pay attention to data analysis and give support to the clients in their decision making. Is the data analysis done in order to develop the supplier's own business and processes or to create added value to customers? Usually companies have strategic-level support decision tools, but they expect the service providers to offer tools for operational-level decision support. Service contracts are based on condition monitoring of equipment and in the next step on data, and then right services are available at the right time. E.g. history data is now only used in troubleshooting but there is potential for forecasting the need of maintenance and using databases better, as well as using life-cycle data. Developing processes and automation systems can be seen as a possibility to develop data management. Now data is collected time-based online. It is easy to share data which is collected by equipment, also analysis and reports to the customer are quite normal actions.

### BUSINESS ECOSYSTEMS

#### *Introduction to ecosystems*

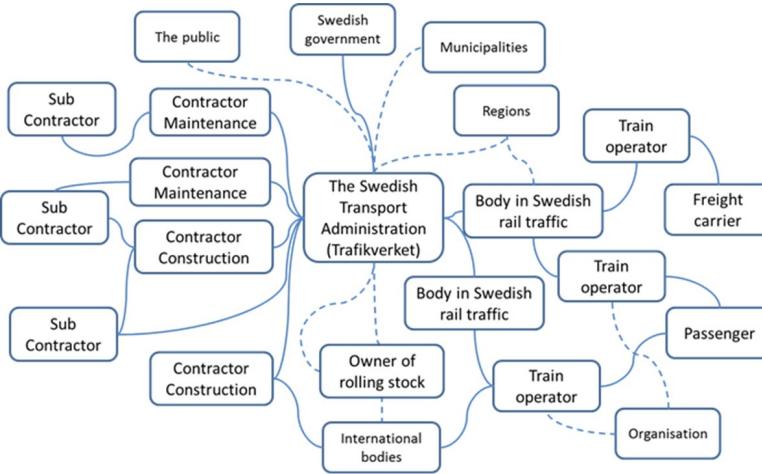
The traditional view of value creation is in the form of a stream, or a chain, where the actors interact by refining input e.g. in the form of raw material to output in the form of a finished product. The value chain could also describe service creation, such as the Swedish railway industry value chain depicted in Figure 2.

In reality, the situation is often more complex than that, as outsourcing and n-party collaborations also connect players to each other in star-like or network patterns [21]. Moore has introduced the concept of business ecosystems as a way to describe the changed business environments characterized by uncertainty and co-evolution [1, 22]. According to [22], a business ecosystem is an economic community consisting of interacting organizations and individuals, which are the organisms of the business world. The ecosystems create value for the customers in the form of goods and services. The traditional actors in a value chain (customers, producers and suppliers) are included in the ecosystem, but also other stakeholders are recognized as actors, such as competitors and public authorities [20].



**Fig. 2 The value chain of the Swedish railway industry**

Source: [20].



**Fig. 3 Business ecosystem, railway traffic in Sweden**

Source: [20].

Figure 3 is an example of a graphical model of an ecosystem describing the Swedish railway industry. Formal relationships between the actors are marked with full lines, while the dotted lines denote informal relationships. In this example the most influential actor, the Swedish Transport Administration, is placed in the middle of the graph.

The business ecosystem is not formalized or fixed in context or time; looking at a limited incision of a business ecology at a particular point in time could reveal business structures with different actors of different power, which changes if the viewpoint or time changes. Moreover, a certain business ecology has different meanings for different actors; for some actors it may be central and to others highly peripheral [23]. New actors might enter and others leave, making the business environment of the ecosystem highly dynamic. The business ecology could be large, and thus it is important to define the limitations, identify the key stakeholders, adapt the value offerings according to the stakeholder requirements, and find out which business models and pricing models are the most viable.

#### *Addressing the barriers and reaching benefits through the ecosystem perspective*

The use of open data sources is accompanied with technical, organizational and cognitive barriers, which hinders the individual actors from reaching the potential benefits. The global and dynamic market forces different actors within asset management to join competences and collaborate in manufacturing service ecosystems [24].

A huge barrier for achieving this is the distrust between the stakeholders; customers are reluctant to share data with the supplier because they are afraid that their business will be in danger. At the same time, many actors lack knowledge of efficient data management. Extending the business environment by adding a neutral information provider and a regulator could be a way to overcome these barriers. The information provider is an actor with knowledge of data management, while the regulator provides support and control mechanisms for the different actors' behavior, including that of the information provider's [2].

The information provider should be a trusted third party with the purpose of managing the asset information for all involved stakeholders for mutual benefits, such as focusing on the core business and development of new business opportunities. A basic premise is that shared data results in data of higher relevance, accuracy and utility for all stakeholders. But it is hard to distinguish relevant data from the large data sets available. Applying the ecosystem perspective lifts the question of what data is relevant to the full value chain level and beyond [1], thus avoiding sub optimization or contradicting goals. The regulator is responsible for creating and governing the holistic view, for instance in the form of common standards, while the information provider enables this process.

Other barriers can be found in the current information systems. The systems are not designed for data sharing, leading to technical difficulties in identifying relevant data sets, fusion of different data sources and creating a coherent database. In addition, parts of the required data are not recorded in the current systems. Hirsch et al. [24] suggest a service-oriented approach to asset management data in the form of Assets as a Service (AaaS). Assets as a Service can be explained as a virtual representation of tangible and intangible assets that facilitate communication and collaboration between actors in the business ecosystem in the form of generic ontologies. AaaS could be used as the basis for creating a holistic process view, as well as for designing information systems supporting data sharing.

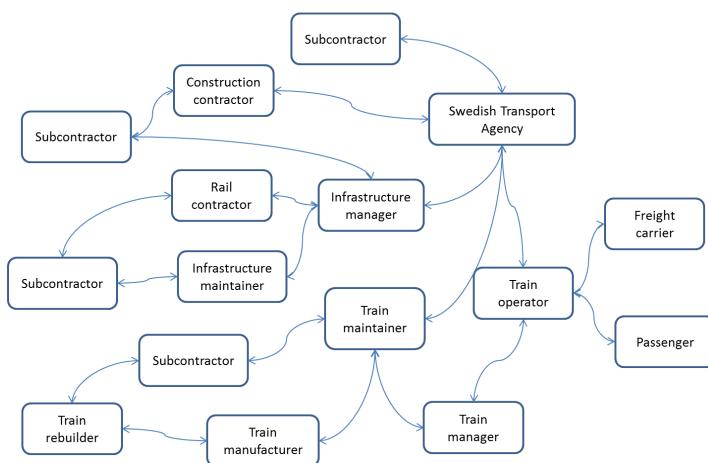
#### *An asset management information example: Swedish railway industry*

The Swedish railway industry is characterized by technical, organizational and operational complexity [25]. Within a period of thirty years, the number of actors in the railway transport industry has increased from less than ten to more than a thousand. Technology advancement for the rolling stock, as well as infrastructure and increased capacity utilization have added to the complexity. The complexity has affected the railway operations as well as maintenance. The root causes of maintenance-related problems have been

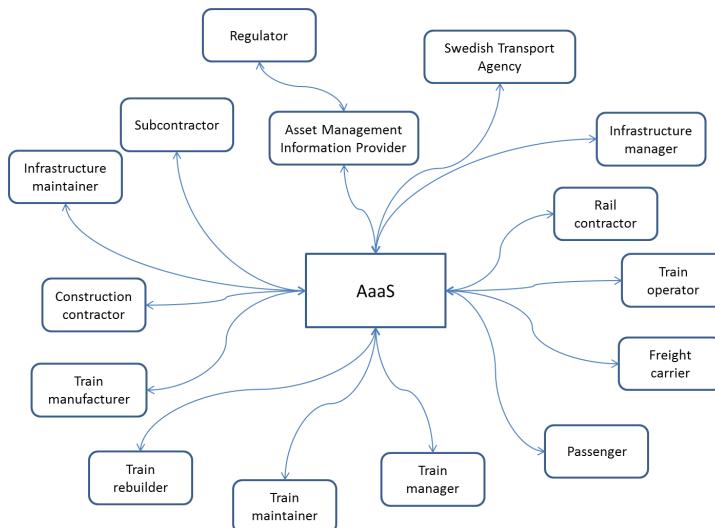
connected to three main areas: information handling and management, regulation and control, and lack of key resources [20]. Among the causes are lack of appropriate IT systems, poor reporting structures, passive governmental management, conservative buyer's culture, poor quality charging system, lack of appropriate maintenance resources, incomplete contractor abilities and competence, and inaccurate analysis models. The tendency is that the actors sub-optimize instead of cooperating. Moreover, traditional contract forms and the conservative buyer's culture result in lack of information and knowledge sharing between the actors [26]. The existing asset information model with the major information flows is presented in Figure 4. Information is shared between the direct actors and regulated in contracts, which results in information isles and interrupted

flows, for instance between the different Subcontractors. Moreover, there exist separation in working areas as well as life cycle phases, resulting in low information transfer between the actors, such as the Infrastructure maintainer and the Train maintainer. Information transfer within the value chain is also affected. The Train maintainer, for instance, has no direct access to failure reports and feedback from the Freight carriers or Passengers. The actors are reluctant to share information that could have business value, either real or perceived.

In Figure 5, AaaS allows for smooth information flows to all actors, which improves information handling and management by the creation of a common asset management ontology for the specific context.



**Fig. 4 Existing asset management model**



**Fig. 5 Alternative asset information management model**

The Asset Management Information Provider organizes the data/information fusion and sharing as to which data is shared and with whom it is shared. This way, the data shared by several actors is available in the appropriate format and distribution form, while the safety and integrity of the data is secured. The Regulator assures the relevancy and accuracy of the AaaS ontology with respect to the overall ecosystem objectives, which are to ensure the traffic to move forward with the promised delivery of quality now and in the future [27]. In the case of the Swedish railway, the Regulator should be assigned by the Swedish government.

## CONCLUSIONS

Data sharing has a good potential, but the ownership of data is perceived as very important to companies. They do not want to share data with others because they are afraid of harmful use of the data. Another barrier is lack of knowledge to analyze big data. Companies do not identify the advantages of data sharing because they do not understand the data well enough, or the possibilities available in combining data. The maintenance playground is complex and fragmented, and all parties have their own computerized systems, making it hard to orchestrate data flows and data sharing. The new solutions must be suitable for integrating with the manufacturers' equipment. A very large amount of data is collected but it is difficult to define what data should be shared. Many doers are afraid that someone else can have more advantages of the shared data which lead to data sharing is not done enough in companies or between companies. Win-win thinking has not become popular in data sharing, and customers do not understand the potential of new services based on data sharing.

In the future, transparency can be seen as a "sharing economy". The big question is how it can be implemented in a multi-company environment with a positive attitude. Data sharing rules must have been agreed with the partners beforehand. Finding an outside facilitator whom all trust could be challenging. The Asset Management Information Provider is an information manager offering the needed information to all actors with Asset as a Service. The problem of trust between the actors can probably be solved with the AaaS concept. Sharing data can create potential for new business, e.g. new services can be developed, such as remote support, data combination and analysis services, etc. The sharing economy adds transparency, which can work positively between companies and service networks. Better data management can help to make better decisions, and online data enables creating new business models, especially for service providers.

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**PhD Student, Lasse Metso**

School of Business and Management,  
Industrial Engineering and Management,  
Lappeenranta University of Technology  
Skinnarilankatu 34, 53850 Lappeenranta, FINLAND  
e-mail: Lasse.Metso@lut.fi

**PhD, Associate Professor, Mirka Kans**

Department of Mechanical Engineering,  
Linnaeus University Växjö  
P G Vejdes väg, 351 95 Växjö, SWEDEN  
e-mail: Mirka.Kans@lnu.se

## **Publication V**

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**Maintenance as a combination of intelligent IT systems and strategies: a literature review**

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## MAINTENANCE AS A COMBINATION OF INTELLIGENT IT SYSTEMS AND STRATEGIES: A LITERATURE REVIEW

Lasse Metso<sup>1</sup>, David Baglee<sup>2</sup>, Salla Marttonen-Arola<sup>2</sup>

<sup>1</sup> Lappeenranta University of Technology, LUT School of Business and Management, Finland

<sup>2</sup> University of Sunderland, Department of Computing, Engineering and Technology, UK

*Corresponding author:*

Lasse Metso

Lappeenranta University of Technology

LUT School of Business and Management

P.O.Box 20, 53851 Lappeenranta, Finland

phone: +358503225383

e-mail: [lasse.metso@lut.fi](mailto:lasse.metso@lut.fi)

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### ABSTRACT

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This study provides a systematic review of the existing academic literature describing the key components of eMaintenance. The current literature is reviewed by utilizing a number of academic databases including Scopus, SpringerLink and ScienceDirect, and Google Search is used to find relevant academic and peer-reviewed journal articles concerning eMaintenance. The literature describes eMaintenance as an advanced maintenance strategy that takes advantage of the Internet, information and communication technologies, wireless technologies and cloud computing. eMaintenance systems are used to provide real time analyses based on real time data to offer a number of solutions and to define maintenance tasks. The collection and analysis of appropriate maintenance and process data are critical to create robust 'maintenance intelligence' and finally improvements in manufacturing costs, safety, environmental impact, and equipment reliability. This paper describes how the scientific discussion on eMaintenance has expanded significantly during the last decade, creating a need for an up-to-date review. As a conclusion, three research gaps in the area of eMaintenance are identified, including evaluating the benefits of eMaintenance, agreeing on a comprehensive definition, and developing tools and structures for cooperative eMaintenance.

### KEYWORDS

eMaintenance, information systems, intelligent manufacturing systems, decision support systems.

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## Introduction

Industries are searching for technological solutions to improve their performance in business. The growth of Information and Communication Technologies (ICT) has helped organizations in using advanced solutions, such as eMaintenance, to manage their processes effectively, in this case their maintenance activities [1]. eMaintenance can be seen as a tool for integrating companies' production and maintenance operations through information technological solutions. Due to the rapid technological development, the research topic of eMaintenance is changing and redirecting its focal point constantly. The purpose of this paper is to provide an accurate and up-to-date evaluation of existing academic liter-

ature, and to identify and describe the key components of eMaintenance.

A number of academic reviews on eMaintenance [2–6] describing the development and implementation of eMaintenance systems have been published over the past decade. For example, the basic ideas of eMaintenance have been presented [5], and Maintenance Management (MM) has been described as composed of the pillar of IT, Maintenance Engineering (ME) and relationship management [6]. Another classification is that MM consists of optimization, models, maintenance techniques, scheduling and IT [2]. eMaintenance defines the strategic vision, organization, service and data architecture, and IT infrastructure [4]. However, a number of joint academic and industrial papers providing an updated view

on eMaintenance systems or parts of them within the context of industrial applications have been published recently [7–9]. This paper reviews the literature and state-of-the-practice on eMaintenance and suggests possible gaps from the point of view of researchers and practitioners. In addition, the paper focuses on information and knowledge management and describes how eMaintenance can improve industrial maintenance to ensure uninterrupted production. The paper puts together a number of definitions for eMaintenance, and conceptualizes its current state. The benefits and barriers of using intelligent maintenance systems are considered as well. The growing importance of the research topic is addressed through studying the trend in the numbers of published scientific articles.

The literature review presented in this paper has been carried out by utilizing a number of academic databases, including Scopus, SpringerLink, ScienceDirect and Google Search. These databases were selected due to the high number of academic and peer-reviewed journal articles available considering eMaintenance. Figure 1 shows the section headings of this paper and the main data sources used. A detailed advanced search was undertaken to ensure that a wide selection of journals was examined.



Fig. 1. Main data sources of the paper.

eMaintenance can be seen as an intelligent and integrated maintenance software system which integrates a company's production, maintenance and other technical management systems [7, 10, 11]. Sophisticated information technologies are used to create intelligent maintenance systems [12, 13].

The structure of the paper is as follows. First, the concept of eMaintenance is introduced with supporting definitions, data sources and the enterprise perspective. Next, scientific articles and web pages about eMaintenance are presented, followed by scientific articles in special issues about eMaintenance and in handbooks, which have a more practical point of view. Then the advantages and challenges of eMaintenance are summarized. Finally, the conclusion describes the main findings of the study and suggests future research targets.

## **Maintenance concept**

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One of the first articles to explain eMaintenance examined a distributed intelligent and integrated system [10]. This system integrated the control, maintenance and technical management activities of a shop-floor organization to an intelligent system, now known as eMaintenance. eMaintenance allows the integration of production and maintenance operation systems. The importance of the maintenance function should be acknowledged, because it can impact the production operations and business process by ensuring system safety and by decreasing the costs of operations during the life time of systems [7].

eMaintenance as a system should be connected to other systems to assist in the collection, analysis and definition of maintenance tasks which take advantage of the idea “right data to right person at right time”. The ‘strength’ of eMaintenance is based on various data sources, and it utilizes different tools and techniques [11].

eMaintenance can be described as an “intelligent maintenance center” because it collects data from a number of different sources and provides relevant data to be used in the development of maintenance tasks. It supports the use of data collection and transfer to remote use through a number of Internet-enabled technologies. eMaintenance technologies can be used with other maintenance strategies to share and exchange information, such as eIntelligence. eIntelligence is a term that covers eMaintenance but also other data and ICT – related aspects of business [12–14].

## **Definitions of eMaintenance**

Various authors have defined eMaintenance as either a concept, a philosophy, or a technology, which makes it difficult to create a unified way of understanding eMaintenance [14]. eMaintenance definitions collected from different journal articles are listed below:

(1) “Transformation system that enables the manufacturing operations systems to achieve predictive near-zero-downtime performance as well as to synchronize with business systems through the use of web-enabled and tether-free (i.e. wireless, web...) infotronics technologies” [15].

(2) “Maintenance support which includes the resources, services and management necessary to enable proactive decision process execution. This support includes e-technologies (i.e. ICT, Web-based, tether-free, wireless, infotronics technologies) but also eMaintenance activities (operations or processes) such as e-monitoring, e-diagnosis, e-prognosis...” [16].

(3) “The network that integrates and synchronises the various maintenance and reliability applications to gather and deliver asset information where it is needed. eMaintenance is a subset of e-manufacturing and e-business” [17].

(4) “eMaintenance is a maintenance management concept where maintenance tasks are managed electronically using real time equipment data obtained over the Internet. It introduces an unprecedented level of transparency and efficiency into the entire industry” [18].

(5) “The appearance of e-technologies allowing the increase of maintenance efficiency, velocity and so on optimising maintenance related workflow (i.e. infotronics technologies)” [4].

(6) “The need to integrate business performance, which imposes to the maintenance area the following requirements: openness, integration and collaboration with the others services of the e-enterprise (new way of thinking maintenance)” [4].

(7) eMaintenance is “the set of maintenance processes that uses the e-technologies to enable proactive decisions in a particular organization” [19].

Based on the definitions presented above, it can be suggested that eMaintenance is a strategy within maintenance, which is supported by the use of ICT and new technologies. It utilizes real-time data from different sources to provide support to decision makers. These definitions show that eMaintenance can be understood in a number of different ways, which all should include advanced software and intelligent sensor systems, thereby providing connectivity and access to specific data. According to Zachman’s framework [20], eMaintenance can be structured to five levels [4]:

- strategic vision,
- business processes,
- organization,
- service and data architecture, and
- IT infrastructure.

Zachman’s framework defines an information system architecture for eMaintenance. The strategic vision supports the scope of eMaintenance, the business processes support the owner’s view of the business, eMaintenance organization supports the architect’s view, the service and data architecture supports the designer’s view, and finally the IT infrastructure supports the builder’s view on the system. eMaintenance has been presented as a concept executed by advanced ICT. It is important to note, however, that this also connects eMaintenance to the strategic vision and business processes of a company.

The main elements of eMaintenance can be identified as:

- base knowledge,
- data acquisition system,
- models (mathematical and statistical), and
- performance reporting [21].

Base knowledge means understanding the physical system to be maintained, as well as the critical features and characteristics from which performance and health can be predicted. The data acquisition system is an ICT system for monitoring the physical system to be maintained. Mathematical and statistical models support decision making in maintenance. They estimate the reliability and remaining lifetime of the physical system, determine the maintenance actions, and plan and schedule the maintenance. The performance reporting system gives reports of eMaintenance, production, and other services. ICT has an integrated network of machines, and the technology enables eMaintenance to share data effectively [21]. It should also be noted that eMaintenance could be intra-organizational or inter-organizational. In fact, eMaintenance allows many manufacturing companies to transfer from product-oriented business to service-oriented business [22].

## Data

The aim of eMaintenance is to connect maintenance and production data with an intelligent system to analyze a number of manufacturing parameters. In effect, it creates a ‘smart factory’ environment. However, to be useful, eMaintenance solutions need to be integrated with other information systems which allow transferring data between different environments. It is important that all systems in the eMaintenance network can exchange information in an efficient and usable way [23]. This is depicted in Fig. 2.

Figure 2 shows that eMaintenance includes monitoring, collection, recording and distribution of real-time data and decision/performance support in-

formation. eMaintenance improves the performance of the maintenance process through effective data collection and distribution. Data is converted into information and then generated to knowledge, which is valuable in the decision-making process [25]. Computerized Maintenance Management Systems (CMMS) allow users to use maintenance data. Maintenance information systems often contain work order control, labor management, equipment management, material control & purchase, and performance report modules [21]. Enterprise Resource Planning (ERP) systems have been used previously in maintenance management to collect, store and analyze manufacturing data [26]. However, eMaintenance is a much wider concept than the relatively narrow modules suggested in ERPs. eMaintenance solutions must have access to different data sources. The integration of different systems can be challenging. Data quality must be taken into consideration, and also interconnectivity is important for eMaintenance solutions, because data is transferred between heterogeneous environments. All systems must be able to interact in an efficient and usable way in eMaintenance solutions [27].

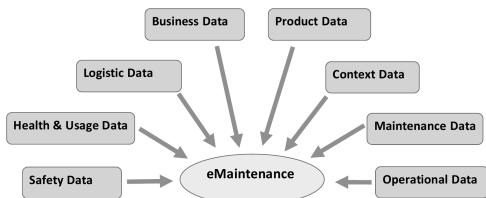


Fig. 2. eMaintenance data access [24].

Traditional “fail and fix” maintenance practices are changing into a perspective of “predict and prevent”. eMaintenance methodology has emerged due to the increase in Internet technologies, faster data transfer and specific data analytics to collect and analyze large amounts of data quickly and effectively. Sensors enable the collection and delivery of data about the status of machines. This data is rarely used to support a continuous information flow throughout entire maintenance processes, because the infrastructures do not support data delivery, management and analysis. A possible answer is to include smart machines in a remotely monitored network, where the data is modeled and analyzed with embedded systems, this should allow a shift from predictive maintenance to intelligent prognostics. Intelligent prognostics is a systematic approach to monitor and predict potential machine failures continuously, and to synchronize maintenance actions with pro-

duction operation, maintenance resources and spare parts [28].

However, data quality from different sources can be inadequate to support maintenance actions. Another issue is technical problems in transferring data from one system to another system. Relevant data is needed, and real-time data and data analysis can improve maintenance actions, but the existing body of knowledge has not yet succeeded in finding optimal solutions to these challenges.

### Enterprise perspective

In this section, the role of eMaintenance is reviewed from the perspective of enterprises, business, and maintenance strategies. According to the standard EN 13306 maintenance strategy means the management method used to achieve the maintenance objectives, e.g. outsourcing maintenance, allocation of resources [29]. Maintenance strategies are directly linked to the performance of maintenance and production. Maintenance strategies can be classified to *reactive strategy*, *proactive strategy* and *aggressive strategy* [30]. However, sometimes maintenance concepts like Total Productive Maintenance (TPM) and Reliability-Centered Maintenance (RCM) are included in maintenance strategies [31]. Reactive strategy can be classified as Corrective Maintenance (CM), proactive strategy can be seen as either Preventive Maintenance (PM) or Predictive Maintenance (PdM), and aggressive strategy can be included in TPM [29].

However, maintenance types can be divided into CM, PM and Improvements in main level, see Fig. 3 [32, 35]. In this paper, the main focus is on PM, Condition-based maintenance (CBM) and on PdM as eMaintenance is based on them.

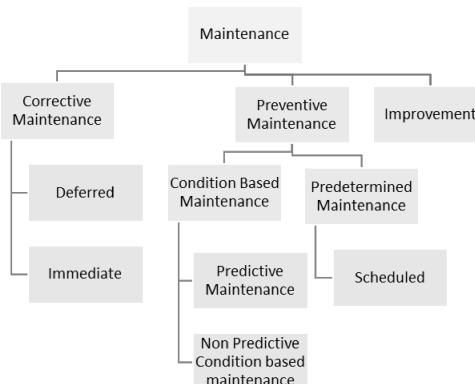


Fig. 3. Maintenance types [29].

Reactive maintenance is often represented as a fire-fighting approach to maintenance. Failed equipment is replaced and then operated until it fails again. Reactive maintenance is usually associated with lower performance. Proactive maintenance strategies try to avoid equipment breakdowns by monitoring the equipment and making minor repairs to keep the equipment in condition. Proactive maintenance strategies are associated with improved performance [33].

CMMS use condition monitoring alarm levels to launch maintenance activities [34]. Condition monitoring and diagnostics are important tools in reducing the costs of production and maintenance. CBM is a strategy that recommends maintenance actions based on monitoring the equipment and therefore information in order to avoid needless maintenance actions [35]. However, a CBM strategy is challenging to implement due to the complexity of remote sensing, data acquisition, data manipulation, state detection, health and prognostic assessment, and generation of advice [36].

CBM is a key component of eMaintenance, having features such as predicting, preventing, and performing maintenance effectively and efficiently [21]. PdM detects early signs of failure in order to make maintenance operations proactive. PdM has been widely adopted in manufacturing and service industries because it can improve reliability, safety, availability, efficiency, and quality. Remote maintenance and eMaintenance support PdM for example in unsafe working environments and dispersed locations.

PdM is a maintenance policy based on the current condition of the system, which is maintained. The potential of PdM is increasing due to the emergence of eMaintenance (or remote maintenance), as well as the growing use of the Internet of Things (IoT) and RFID in maintenance [37].

The current sensor boards contain different types of radio frequency connectivity, e.g. Bluetooth or WiFi. The wireless sensor networks are easy to scale, and it is easy to replace a node. The main advantage of using wireless sensor nodes is the fact that the network is simple to design and easy to install and scale, because a new node can be added easily [38, 39]. CBM monitors the condition of machines with technologies such as vibration analysis, infrared thermography, oil analysis, ultrasonics, motor current analysis, performance monitoring, and visual inspection [34].

The technical infrastructure of eMaintenance consists of different components: hardware, software and hybrid components. IT enables running the applications, communication between the applications, and the execution of needed applications at all levels of the organization. From the point of view of eMaintenance, the IT infrastructure consists of one or more network(s) with servers, workstations, applications and databases, as well as sensors, a Personal Digital Assistant (PDA), Radio-frequency Identification (RFID), and the Global Positioning System (GPS) [14].

It is shown in Fig. 4 how eMaintenance can be implemented to support a company's operations and

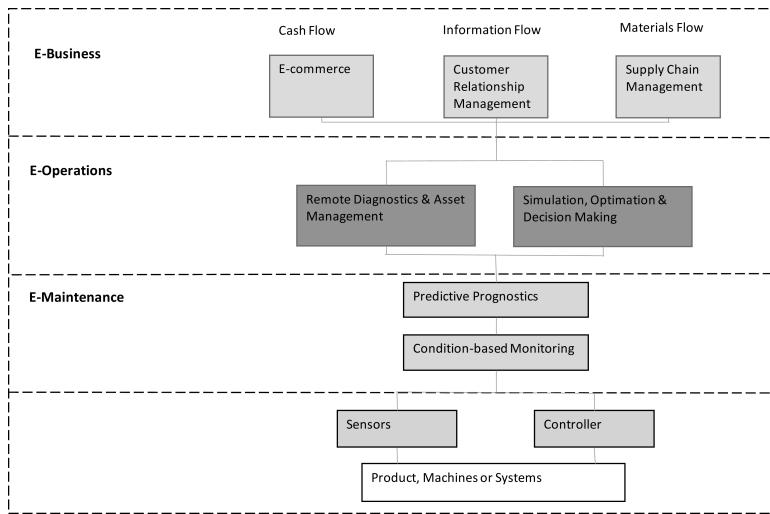


Fig. 4. Enterprise view of eMaintenance [15].

business. In this figure, eMaintenance is presented as CBM and prognostics. Diagnostics is a part of operations, and e-business consists of e-commerce, CRM and Supply Chain Management (SCM). eMaintenance can be considered as a maintenance plan which faces the future automated manufacturing world by CBM, predictive prognostics, remote maintenance and service support, provision of real-time information access, and the integration of maintenance with production. Information flows to all parts can be organized.

eMaintenance can offer low risk and low cost integration of enabling technologies in maintenance processes and activities. Key enabling technologies are for example web services, wireless networks, portable devices, wired and wireless sensors, Micro-Electro-Mechanical Systems, and Radio-Frequency Identification (RFID) [1, 40]. Also Personal Digital Assistants (PDA) have increased reliability, efficiency and safety in maintenance [11].

Maintenance activities are often outsourced, which makes it difficult for service providers to obtain sensor data, as the companies owning the assets are sensitive to sharing their data. However, the service providers would often have the best knowledge to analyze the sensor data to support asset maintenance. Successful implementation of the technologies in industrial environments also requires improvements to managerial and organizational processes.

## Scientific articles and web pages

eMaintenance addresses the fundamental needs of predictive intelligence tools for monitoring the degradation of the assets. This approach has raised growing interest from both the academia and industrial practitioners. In 2005, an Internet search with the Google Search tool identified approximately 2.15 million articles in which the expression “eMaintenance” appeared. By 2015 this had increased to approximately 62.3 million articles. However, within in the citation database Scopus, articles discussing eMaintenance increased year by year until 2010, after which the number of articles declined. In the Springer and ScienceDirect databases the growth continues. This growth is due to the fact that IT has become available at low cost and has been developing rapidly [2].

The Scopus, SpringerLink and ScienceDirect databases were examined to ensure that the review would include the most relevant papers in the academic literature. In addition, a more general search in the Internet was carried out with Google Search. In Fig. 5, the number of articles in the databases is on the left and the number of Google Search hits on the right. The results for 2016 include two months of the year, depicted by the falling curve.

The scale on the right is the search of web pages mentioning eMaintenance. This search was done by

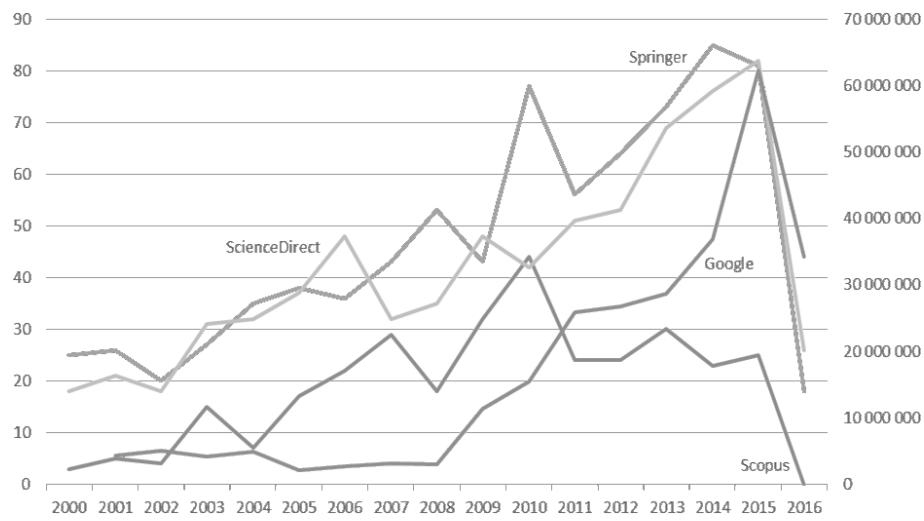


Fig. 5. Publications in databases per year.

Google Search. The Google search included all web pages that contained the search word “eMaintenance” written in a number of different ways, giving 62,300,000 hits for 2015. The key attributes of data quality are accuracy, correctness, currency, completeness, and relevance. As regards the search results, it is possible that the data quality was to some extent incomplete (some web pages could have been counted many times, some webpages might have been missing, and the number of hits changes because the web pages are not available all the time). However, the exact number of web pages is not the most important finding here, what is important and interesting is the growing trend of web pages about eMaintenance.

A classification has been made in the field of maintenance management based on available scientific literature. Garg and Deshmukh [2] divided the existing maintenance management research into six areas: (A) maintenance optimization, (B) maintenance techniques, (C) maintenance scheduling, (D) maintenance performance measurement, (E) maintenance information systems, and (F) maintenance policies. Before this, the classification of maintenance management was limited in the literature. Various trends have been suggested to help researchers to identify gaps in the literature and maintenance professionals to understand maintenance management. With regard to eMaintenance, the results of Garg and Deshmukh’s study [2] are interesting. 142 papers were analyzed, out of which only 6 papers dealt with maintenance systems. An interesting feature in this review was that the word “eMaintenance” was not included, either in the review paper or in the titles of the references. Thus, as figure 5 shows, the main body of knowledge on eMaintenance has developed rapidly during the last decade, and there is a clear need for an up-to-date review to study the current research trends and possible gaps.

### **Special issues in eMaintenance**

In 2006, Computers in Industry published a Special issue on eMaintenance. It contained 10 articles examining eMaintenance, presented in Table 1.

In the 10 scientific articles about eMaintenance listed in Table 1, the most often used key words were: “eMaintenance” (mentioned 5 times), “predictive maintenance” and “condition monitoring” (both mentioned 3 times), as well as “neural networks”, “diagnosis”, and “artificial intelligence” (2 times each). All the other key words were used only once, although some of them were quite closely connected with each other. Most of the interrelat-

ed keywords focused on for instance *remote use* of systems (keywords like “remote monitoring”, “distant system”, “monitoring”, “remote maintenance”, and “concurrent engineering”). Another group of key words was related to *maintenance policies* with keywords like “service integration”, “strategic planning”, “eMaintenance service”, and “maintenance engineering”. The third group was related to *intelligent ICT* systems (keywords like “artificial intelligence”, “application integration”, “health condition”, “intelligent system”, “CMMS”, and “UML”). The forth group was related to *analysis of maintenance* with keywords like “diagnosis”, “prognostics”, “detection”, “fault latency”, “fault diagnosis”, “novelty detection”, “fault tree”, “alarms” and “criticality analysis”. The rest of the key words were difficult to group, so they are only listed here: “spare part manufacturing”, “logistic support”, “discrete-event systems”, “timed automata”, “neuro-fuzzy”, “maintenance”, “SCADA (Supervisory Control and Data Acquisition)”, “FMECA (Failure Modes Effects and Critical Analysis)”, “maintenance effectiveness”, “induction motors”, “simulation” and “benchmarking”.

On the basis of the above, it can be seen that eMaintenance uses condition monitoring and analysis to execute predictive maintenance. Also technical systems, including neural networks and intelligent ICT systems, are used in eMaintenance. According to the topics presented in the Special issue on eMaintenance, the main components of eMaintenance include predictive maintenance, condition monitoring, intelligence in the network, remote operations, maintenance policies, and analysis.

In 2014, the *Journal of Quality in Maintenance Engineering* published a *Special Issue: Condition Monitoring and eMaintenance*. The special issue contained 6 articles about eMaintenance, which are presented in Table 2.

In the 6 scientific articles listed in Table 2, the key words mentioned several times were: “eMaintenance” (4 times), “maintenance” (3 times), “railway” (2 times) and “information and communication technologies” (2 times). There were keyword groups like *ICT-related*, maintenance measurement, decision support and others. The *ICT-related* group included “Web 2.0”, “Cloud computing”, “agent technologies”, “online”, “cloud”, and “CMMS”. Cloud computing is a technology that is dynamically scalable, and resources are provided as a service over the Internet. The keywords relating to *maintenance measurement* were: “prognostic health management”, “availability performance”, “dependability improvement”, “dependability”, and “performance measurement”. “Usability” and “user interface” are close to each oth-

er. In this special issue there was a more ICT-related view to eMaintenance than in the previous journal presented in table 1. The same kinds of things were of course presented, but now much more ICT technologies

were included. This could mean that ICT had developed in 8 years so quickly that these systems were more developed than before. Also usability and user interfaces were taken into account.

Table 1  
Computers in Industry, Special issue on eMaintenance (2006).

Title	Authors	Key Topics
Intelligent prognostics tools and e-maintenance	Jay Lee, Jun Ni, Dragan Djurdjanovic, Hai Qiu, Haitao Liao	Develops predictive tools and intelligent maintenance systems, smart prognostics, performance prediction, diagnosis and assessment, CBM, Watchdog Agent
Envisioning e-logistics developments; Making spare parts in situ and on demand; State of the art and guidelines for future developments	François Pérès, Daniel Noyes	Presents a concept of spare part manufacturing, isolated systems, quick manufacturing technologies using eMaintenance support, e-logistics development based on freeform technologies manufacturing spare parts on request and in a short time, rapid prototyping, rapid spare part manufacturing
Monitoring and predictive maintenance; Modeling and analysis of fault latency	Zineb Simeu-Abazi, Zouhir Bouredji	Proposes a new way of modeling complex systems, monitoring the manufacturing system, evaluation of fault latency and performance, fault analysis
Flexible software for condition monitoring, incorporating novelty detection and diagnostics	Christos Emmanouilidis, Erkki Jantunen, John MacIntyre	Investigates a flexible monitoring and diagnostic system, novelty detection, diagnosis of software, database structure, novelty identification and machinery diagnostics, independent software modules, such as the Fault and Symptom Tree, the Fuzzy Classification module, the Novelty Detection and the Neural Network Diagnostics sub-systems, CBM
A neuro-fuzzy monitoring system; Application to flexible production systems	Nicolas Palluat, Daniel Racoceanu, Noureddine Zerhouni	Investigates a new method for developing a neuro-fuzzy monitoring system supporting a diagnosis aid system combining neural network learning capabilities and natural language formalism, UML
PROTEUS – Creating distributed maintenance systems through an integration platform	Thomas Bangemann, Xavier Rebeuf, Denis Reboul, Andreas Schulze, Jacek Szymanski, Jean-Pierre Thomesse, Mario Thron, Noureddine Zerhouni	Presents a maintenance-oriented platform, the architecture and basic concepts of an integration platform, remote maintenance, implementation of several system components, design and implementation of maintenance workflow, global access and communication
SIMAP: Intelligent System for Predictive Maintenance; Application to health condition monitoring of a wind turbine gearbox	Mari Cruz Garcia, Miguel A. Sanz-Bobi, Javier del Pico	Studies the diagnosis of real-time industrial processes, proposes an intelligent system for predictive maintenance, which takes account of the information coming from different sensors and other information sources in real time and tries to detect possible anomalies in the normal behavior expected of the industrial components, maintenance scheduling
Development of an e-maintenance system integrating advanced techniques	Tian Han, Bo-Suk Yang	Investigates a new e-maintenance system which enables manufacturing operations to achieve near-zero-downtime performance on a sharable, quick and convenient platform, condition monitoring, fault diagnosis
Information requirements for e-maintenance strategic planning; A benchmark study in complex production systems	Marco Macchi, Marco Garetti	Presents a benchmark study in complex production systems materializing information requirements for eMaintenance strategic planning, maintenance logistic operations and cost optimization
An intelligent maintenance system for continuous cost-based prioritisation of maintenance activities	Will J. Moore, Andrew Starr	Investigates a strategy called cost-based criticality (CBC), condition monitoring, up-to-date cost information and risk factors, allowing an optimized prioritization of maintenance activities, combines information about the technical state or machine health, cost of maintenance activities or loss of production, and non-technical risk factors, such as customer information

Table 2  
Journal of Quality in Maintenance Engineering, Special Issue: Condition Monitoring and eMaintenance (2014).

Title	Authors	Key Topics
Condition monitoring and e-maintenance solution of railway wheels	Matthias Asplund, Stephen Famurewa, Matti Rantatalo	Study of failures in train wheels, analysis of factors that correlate with the high occurrence of wheel defects, such as temperature, travelling directions, different vehicles, wheel condition monitoring
Current and prospective information and communication technologies for the e-maintenance applications	Jaime Campos	ICTs in condition monitoring, Web 2.0 technologies, Cloud computing, agent technologies, MaaS (Maintenance as a Service)
Information logistics for continuous dependability improvement	Peter Söderholm, Per Norrbin	Study of improvement in the performance of the Swedish railway system, information logistics and technologies to support continuous monitoring, reliability performance, maintenance support performance, maintainability performance, technical systems, quality of service
eMaintenance solution through online data analysis for railway maintenance decision-making	Ravdeep Kour, Phillip Tretten, Ramin Karim	eMaintenance solution in the railway sector, cloud and web applications, data visualization, visualization of train wheel maintenance and safety limits, on line data analysis, decision making
Measuring performance of linear assets considering their spatial extension	Christer Stenström, Aditya Parida	Investigation of how the performance of linear assets can be analyzed and displayed, technical asset and user context, asset management at strategic, tactical and operational levels, linking together the technical and operational levels to measure asset performance, failures and costs, visualizing performance, improving the analysis
Enhancing the usability of maintenance data in management systems	Phillip Tretten, Ramin Karim	Study of eMaintenance solutions, CMMS, eMaintenance in aviation and industry, poor usability, industrial and aircraft maintenance needs are identified, improvement ideas to develop maintenance systems are presented

An important issue with the existing eMaintenance articles seems to be that they present concepts or models which are not tested in practise, nor developed further. Of course, there are many authors who publish research results continuously and develop models with their research teams all the time, but this kind of long-term perspective is often missing from individual publications.

## Handbooks

As the literature on eMaintenance has extended, there has been an increase in the number of handbooks published on the topic. An *eMaintenance* book [22] containing 16 chapters was published in 2010. This book describes maintenance trends, information and communication technologies in maintenance, intelligent sensors, mobile devices and wireless communication in maintenance, as well as strategies and decision support systems in maintenance. Also industrial solutions of eMaintenance and eTraining are included in the book. In this handbook, the state of the art is reviewed, and the development of techniques and methods are presented. In addition, the

book reports on laboratory testing as well as the use of eMaintenance in industry.

The *Maintenance Engineering Handbook* [41] covers the most commonly discussed aspects of maintenance engineering, e.g. the organization and management of maintenance functions, best practices in predictive maintenance, engineering and analysis tools, and it also provides an update to the latest technologies and methods. Also handbooks entitled *Complex System Maintenance Handbook* [42] and *Handbook of Maintenance Management and Engineering* [8] include a section on eMaintenance.

*Maintenance, Replacement, and Reliability: theory and applications* offers tools to making decisions in maintenance [9]. The book includes models relating spare parts and CBM. This book addresses maintenance in general, not just from the perspective of eMaintenance. There are also a number of books on maintenance which do not discuss eMaintenance, including *The Handbook of Maintenance Management* [43] and *Handbook of Performativity Engineering* [44].

On the basis of the literature search, it can be argued that the majority of handbooks and scientific

articles present eMaintenance in quite a similar way. However, the majority of handbooks provide a basic approach and less technical knowledge, while scientific articles focus on a specific model or clearly defined technical issues.

## Advantages and challenges in eMaintenance

The advantages and challenges of eMaintenance are presented in Table 3. It should be noted that the same main items can be seen as both advantages and challenges for eMaintenance, e.g. in theme 3, inspection and monitoring are difficult if real-time, remote and distributed monitoring and analysis devices have not been developed [5, 16].

eMaintenance offers possibilities to improve the development of new ways of implementing maintenance. Maintenance expert centers can be organized easily because data can be shared easily over the Internet. Experts can log in to systems remotely and give their instructions to maintenance employees. Maintenance support can be improved, and real-time data should always be available. Maintenance docu-

mentation should always be updated and available because the users could log in to systems anywhere with any equipment. This is naturally an issue of security because eMaintenance is used over the Internet, and the same security risks exist as in other Internet-based solutions. Also transparency and access to maintenance information and services across the maintenance operation chain has been seen as a benefit in eMaintenance [38].

The positive impact of eMaintenance can be divided into two levels. The first is the ‘maintenance micro-level’, where eMaintenance serves technicians, mechanics and support engineers as a support to execute maintenance tasks. eMaintenance reduces the number of interfaces to information sources, improves fault diagnosis and knowledge sharing, and automates the procedures of technical administration. The second level is the ‘maintenance macro-level’, where eMaintenance supports managerial maintenance planning, preparation and assessment. It enables information-driven maintenance and support processes. In e.g. aviation maintenance, eMaintenance implementation enables a more efficient use of digital product information and design data over the whole life cycle [25].

Table 3  
Advantages and challenges of eMaintenance (Modified from Crespo-Marquez and Iung [16], Muller et al. [5]).

Potential improvements:	Challenges:
<i>Theme 1: Developing new maintenance types and strategies</i>	
Remote maintenance operations and decision making; logging in anywhere and any devices, manpower on the customer's site can be reduced, the use of expertise is easy, new features can be added	Remote maintenance; security and reliability over the Internet, human resource training, maintenance agreements
Business process integration and cooperative/collaborative maintenance; easy to design and synchronize maintenance with production, maximizing process throughput	Business process integration and cooperative/collaborative maintenance; data transform mechanism, communication, data protocols, safe network, the maintenance processes must be stable and capable
Fast online maintenance; real-time remote monitoring, alerts, high rate communication to experts, maintenance support system	
Predictive maintenance; prognostics and health management systems	Predictive maintenance; difficult to integrate different techniques
<i>Theme 2: Improving maintenance support and tools</i>	
Fault / Failure analysis; development in sensors, signal processing, ICT, etc.	
Maintenance documentation; easy to fill out forms, remove bottlenecks between the plant floor and business system	Maintenance documentation; need to collect, record and store information from different systems, multi-tasking and multi-user operating environment
<i>Theme 3: Improving the maintenance activities</i>	
Fault diagnosis / Localization; e-diagnosis offers on-line fault diagnosis for experts	Inspection / Monitoring; problems with distributed monitoring
Repair / Rebuilding; reducing downtimes by direct interaction	Modification / Improvement – Knowledge capitalization and management; how to realize the knowledge-based operation and maintenance of plants

This section is based on an advanced search on articles that have been published recently in scientific journals which focus on the use of the ontologies related to eMaintenance to improve and control data quality. eMaintenance ontologies define the description of ontology, the scope of eMaintenance and the data production phase. E.g. MIMOSA provides metadata, the scope is measurement and CBM data transfer, and the phase is data collection and transfer. Other ontologies in eMaintenance are: OPC UA, PLCS, ISA-95, XML, STEP, CORBA, OAGIS, DPWS, S1000D, S4000M, SOA, SCADA, ATA iSpec2200, and DAIS, HDAIS. eMaintenance ontologies are related to the content structure and communication interface. eMaintenance ontologies produce high-quality data in maintenance, and the maintenance data production process helps to control data quality. However, there are challenges in enterprises to find expertise and enough knowledge to use eMaintenance tools. That is why the tools are not commonly used in enterprises, or they are used ineffectively. Interoperability and data quality are important for both maintenance and operations. Effective decision making requires interoperability at all organizational levels. The use of eMaintenance ontologies increases the economic benefits and enhances decision making [27].

eMaintenance solutions tend to suffer from poor usability [45]. The following actions would be needed to enhance the usability:

- improving access to documents,
- adding compatibility with other systems,
- minimizing manual work,
- making the User Interfaces better,
- making it easier to use databases,
- improving the support in maintenance decision making, and
- improving the complexity of software [46].

## Conclusion

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It is clear that production maintenance is a very important area for manufacturing industries. The key components introduced by eMaintenance are advanced use of ICT, integration of different data sources, expert centers and support to decision makers, as well as combining production and maintenance data. The integration of production and maintenance systems should support the use of real-time information via the Internet.

Based on the literature review presented in this paper, three research gaps can be identified in the state of knowledge in eMaintenance. The first gap is related to the various disjointed definitions of eMain-

tenance, which cause the research field to be somewhat fragmented. As a result, eMaintenance can be addressed from a variety of perspectives, including for example maintenance strategies and ICT. Partly because of this, also companies seem to use the term in various ways. More research and industry-academia cooperation would be needed to create a widely accepted eMaintenance concept in practice. On the other hand, the increase in the number of articles, Web pages and handbooks about eMaintenance demonstrate a growing interest and importance of eMaintenance for both the academia and industry. Thus, comprehensive, up-to-date terminology would be needed to integrate the different aspects of eMaintenance and to increase the understanding of the subject as a whole.

The second research gap is related to the assumed benefits of eMaintenance. This paper has listed the advantages of eMaintenance, but in practice it is difficult to measure these advantages and to prove that they exist. Finally, the third research gap is related to cooperative eMaintenance. There is a need to create novel, joint processes and structures (e.g. data security, system interoperability, and management of maintenance documentation) for both practitioners and academics in eMaintenance service networks. There are security tools to ensure the safety, e.g. security policies, firewalls and intrusion detection systems/prevention systems, artificial immune systems, and cloud computing [47]. Security in eMaintenance systems must be planned carefully before implementing the system. The issues to be considered include e.g.: Who should have access to the system? How are the network connections arranged? If data ownership is unclear, an agreement must be done about who owns the data. Are the sensors and other equipment secure for information security? How are transmissions from one system to another system done? Both the second and the third research gap imply that in the future, the research perspectives (including e.g. maintenance engineering, ICT, and data sciences) traditionally adopted in eMaintenance should be supported by management research to overcome the challenges in the implementation of eMaintenance solutions.

This paper offers two main theoretical contributions. Firstly, previous research and knowledge on eMaintenance has been reviewed and summarized, contributing to increasing the understanding of the research topic with significantly increased importance and scope. Secondly, three research gaps have been identified in the literature on eMaintenance, providing researchers a clearer view of the current state of the scientific knowledge in the topic.

The managerial implications of the paper also include two main aspects. Firstly, the key concepts and current state of research on eMaintenance have been analyzed, providing managers a summary of the various perspectives of the topic. The paper presents the potential of eMaintenance in developing maintenance, the advantages and challenges of eMaintenance, and ICT technologies used in eMaintenance. Secondly, the paper has shown the interdisciplinary nature of eMaintenance, and it contributes to managerial decision making through suggesting eMaintenance as a combination of maintenance, ICT, data sciences, and management knowhow. Mathematical and statistical models are used in eMaintenance to support decision-making. Data is collected from networked equipment and from other software systems, and remote access enables the use of internal and external experts to support decision-making.

The paper has highlighted the fact that eMaintenance can support innovation, automation and sophisticated processes for maintenance and has proven to be critical for organizations in maintaining a leading position. However, the question remains, what will happen next? The use of technology to promote increased computerization and the integration of industrial systems requires a new approach to create an interconnected factory of machines, systems, humans, as well as the environment to create an intelligent self-controlled network spanning the entire value chain. In the ideal factory, machines react to unexpected changes autonomously in production, predict failures, and trigger maintenance processes. However, eMaintenance does not remove all human issues in maintenance, for example problems in communication, attitude, or the organization's way to do things are not issues eMaintenance systems have an influence in.

“Industry 4.0” the fourth industrial revolution has been growing slowly in Europe. Focusing on cyber-physical systems, Industry 4.0 is regarded as the next-generation production framework which uses the advances in information technology, autonomous engineering, the Internet of things, cloud infrastructure, and big data for manufacturing, as well as new technologies such as additive manufacturing. Using Industry 4.0 and eMaintenance techniques will create seamless communication between products and machines to enable self-steering, flexible and efficient production processes and therefore support new asset management initiatives.

The limitations of this paper are mostly related to the wide scope and rapid development of the research topic. It can be assumed that the results are sensitive to time and that the state of the knowledge

on eMaintenance can change a lot even in a short time. In addition, the wide scope of the topic made it impossible to analyze all the relevant literature. For instance, the state of knowledge in companies was mostly left out in this paper. The term eMaintenance is widely used in companies, but it can have a slightly different meaning than in academic papers. There are companies for which eMaintenance is a service that can be ordered via the Internet [48]. Bigger companies tend to see eMaintenance in a similar way as presented in academic papers, consisting of data collection, data storing, data sharing, remote control, remote access, and so on. Due to these limitations, it is recommended that an up-to-date review of the topic is published periodically. In addition, the paper identified gaps in the research on eMaintenance, but finding explicit solutions to them was deemed to be outside of the scope of this paper. Thus, contributing to the gaps is left for further research.

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