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

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ABSTRACT
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.

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 literature, 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.

eMaintenance concept
• Databases

Number of articles
• Databases and Internet

Special issues
• Databases

Handbooks
• Internet

eMaintenance in enterprices
• Internet

Advantages and challenges
• Databases

Areas of improvement
• Advanced search, new articles

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.

eMaintenance concept

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].
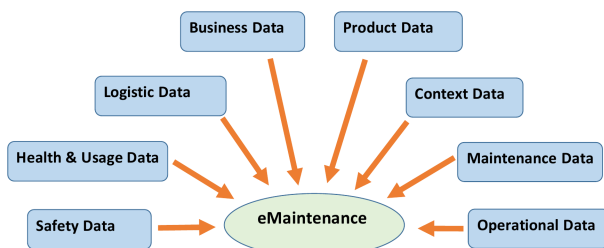

Fig. 2. eMaintenance data access [24].

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.
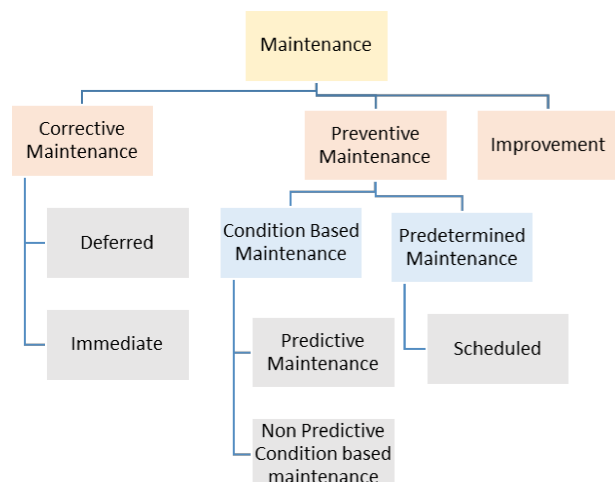

Fig. 3. Maintenance types [29].

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
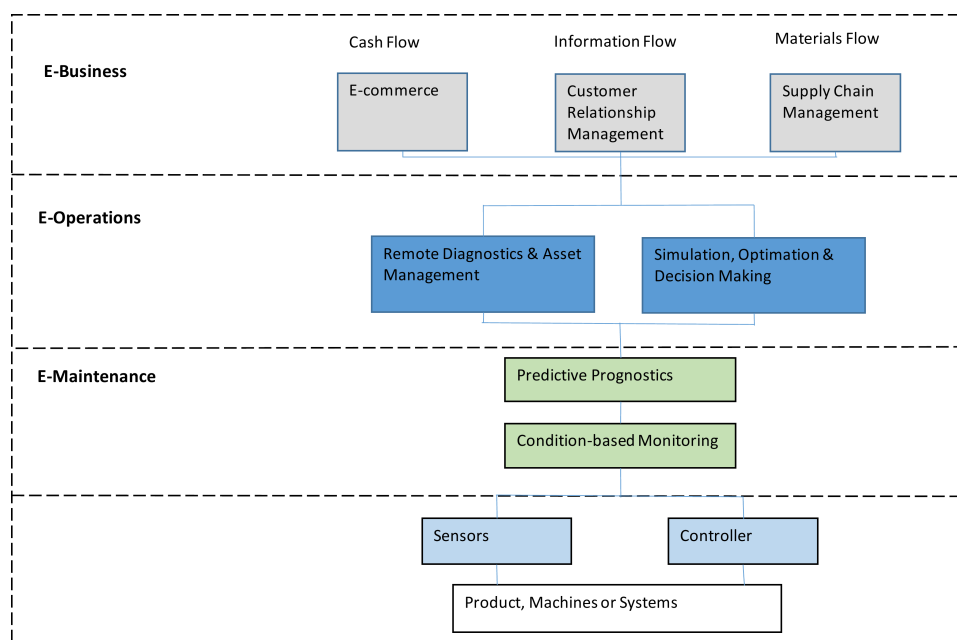

Fig. 4. Enterprise view of eMaintenance [15].

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 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.

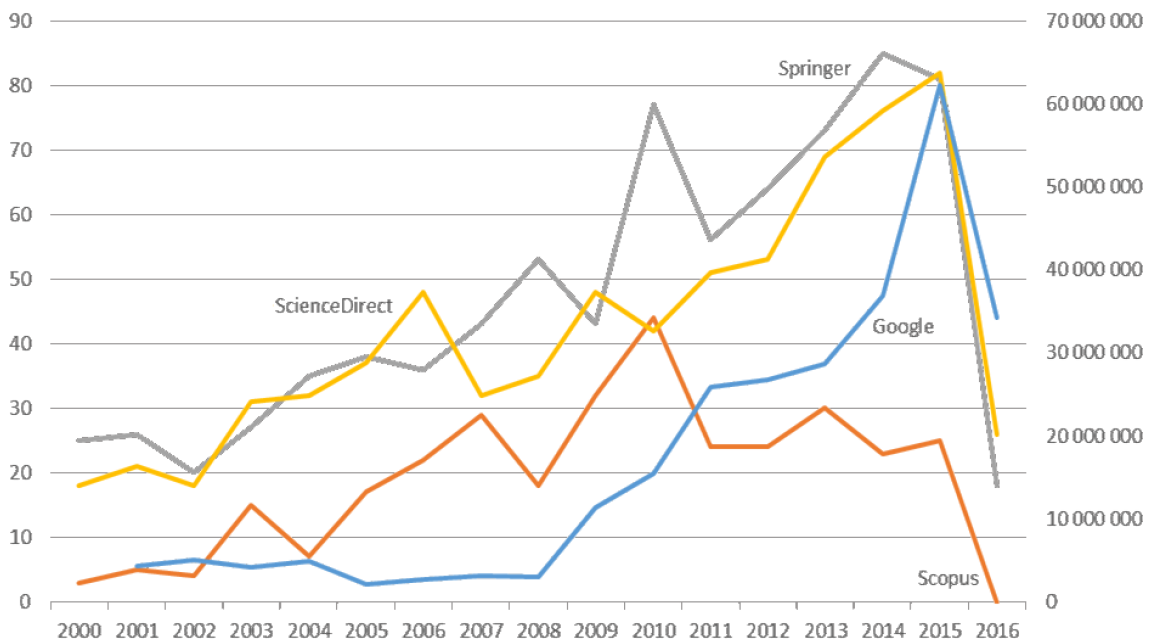The scale on the right is the search of web pages mentioning eMaintenance. This search was done by

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 Performability 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:
Theme 1: Developing new maintenance types and strategies	
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
Theme 2: Improving maintenance support and tools	
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
Theme 3: Improving the maintenance activities	
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

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 is 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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