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OPERATIONS, INFORMATION & TECHNOLOGY | REVIEW ARTICLE

Managing the information systems in the industrial domain

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Abstract: The purpose of the paper is to understand the developments of the Information Systems (IS) and Information technology, i.e. Information and Communication Technologies (ICTs) in the area of Condition Monitoring and Maintenance, especially e-maintenance. Therefore, the paper goes through and categorises the literature findings with the support of two models, i.e. the three era and the IS capability models to analyse and understand the maturity of the ICTs in the domain. The result shows that many researchers are working with software applications that are in the data processing era, which is highly important for the technologies and then the management of IS era. Conversely, both in the Management Information Systems and the Strategic Thinking era fewer findings have been made so far. Further on, in the fourth era, named the Information System (IS) capability, the research findings are mostly at the rudimentary stage. The implementation of Web technologies, such as the Web 2.0, i.e. Social media technologies, can facilitate the learning aspects in the maintenance department as well as collaboration between employees, which are important aspects of the last era, i.e. in the IS capability era. The paper highlights interesting organisational as well as ICT aspects that should be considered when planning, developing and implementing the e-maintenance IS.

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PUBLIC INTEREST STATEMENT

The competition on the market is one of the key reasons that lead inevitably companies to invest in various Information and communication technologies (ICTs) with the purpose to reinforce their strategies and different processes to keep ahead of the competition. It is, however, crucial to implement the proper ICTs for the company in question to be able to contribute with a foundation of an increased competitive advantage. Therefore, this article goes through the use of different models to understand the current state of maturity of the ICTs in the industrial domain, especially in the maintenance department. Consequently, the paper highlights different challenges in the light of recent research developments and uncovers, for instance, cogent reasons for these obstacles providing explanations and recommendations on how to overcome them. This in its turn is rather important since companies that are able to manage such issues successfully are therefore able to increase their organisational performance.

Subjects: Information & Communication Technology (ICT); Management of IT; Technology

Keywords: web technologies; Web 2.0; management information systems; strategic planning for information systems; IS capabilities

1. Introduction

It is crucial to evaluate various Information Systems (IS) and Information technology (IT), i.e. Information and Communication Technologies (ICTs) used in a company and how they provide different employees with the right data, information and knowledge they need in different situations. It is argued that the organisational resources, such as information and knowledge, are issues that can create problems for companies if not managed well (Nonaka & Takeuchi, 1995; Turban, 1995). Consequently, this can be attributed to the fact that new technologies are needed to enhance the decision-making process as well as to deliver new information and knowledge to the organisation. Therefore, companies that are not executing this could lose their competitive advantage and the ability to compete under the same conditions as their competitors, reduce market shares and diminish profitability. Moreover, the more complete information and knowledge a company has regarding different situations, the more accurate decisions it takes. In such a situation, the decision-maker can be viewed as a perfect predictor of the future (Turban, 1995). In the area of Condition Monitoring (CM) and Maintenance, especially e-maintenance, there have been many efforts made by academia and industry and various maintenance systems have been developed such as ENIGMA, CASIP, ICASAME, Remote Data Sentinel, INTERMOR, INID, IPDSS, WSDF, MRPOS, PROTEUS and TELMA (Muller, Crespo-Marquez, & Iung, 2008). In this process, various ICTs have been applied, for instance artificial intelligence, in CM and Maintenance (Kalogirou, 2003; Marwala, 2012; Nadakatti, Ramachandra, & Kumar, 2008; Patel & Prajapati, 2011; Shu-Hsien Liao, 2005; Wang, 2003; Warwick, Ekwue, & Aggarwal, 1997). Further, Pintelon, Du Preez, and Van Puyvelde (1999) discusses the opportunities that the IT has brought into the maintenance management area. Thus, the emerging opportunities, benefits and difficulties with the integration of the mobile ICT solutions for industrial assets and various processes should be taken into account (Emmanouilidis, Liyanage, & Jantunen, 2009). The current state of affairs when it comes to the developments of ICT in CM and Maintenance can be found in the publication by Campos and Prakash (2006b) and the updated version in the article by Campos (2009). The following work, which is about business strategies within the maintenance management domain, is worth particular attention (Prajapati, Bechtel, & Ganesan, 2012). This is due to the fact that the authors present the maintenance strategies, especially the CBM, which in its turn is categorised under preventive maintenance and is the strategy that is normally connected to the e-maintenance concept with modules such as diagnostics and prognostics. In addition, the authors provide information about recent developments, applications and research challenges in the CBM domain and how the CBM can be used to optimise the maintenance strategies. Various techniques, models and algorithms are used when CBM is implemented following the main steps of the approach, i.e. data acquisition, data processing (DP) and maintenance decision-making (Jardine, Lin, & Banjevic, 2006). In this regard, Sherwin (2000) reviews various models for maintenance management and highlights a substantial contribution of IT to maintenance management. Moreover, the economic and technical aspects within the e-maintenance concept as well as the strategic importance of the maintenance function should be thoroughly considered (Jantunen, Adgar, Emmanouilidis, & Arnaiz, 2010a).

Therefore, four major strategic dimensions of maintenance management are to be outlined, i.e. service delivery options, organisation and work structuring, maintenance methodology and support systems (Tsang, 2002). A crucial aspect of maintenance management for its various decisions depends on the availability of relevant, good quality as well as timely data that is captured by the ICTs. Consequently, the positive impact of the IS and ICTs on maintenance and thereby on productivity has lately been realised by both academia and industry, and a new concept, namely e-maintenance, has been coined. It is defined as “a maintenance management concept whereby assets are monitored and managed over the Internet” Iung (2006). The emerging e-maintenance concept exploits and optimises the potential of the digital technologies. Moreover, when it comes to supporting the e-maintenance through services, processes, organisation and infrastructure, one is supposed to

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investigate the nature of the e-maintenance notion (Levrat, Iung, & Marquez, 2008). In this light the above-mentioned concept is regarded to be revolutionary (Crespo-Márquez, 2008). There have been also determined numerous important both industrial and academic future research directions for possible developments of the e-maintenance applications. One of the directions is that the e-maintenance platform must be based on collaboration and cooperation capacities to support well the new services (Iung, Levrat, Marquez, & Erbe, 2009). In addition, important issues of the e-maintenance approach can be found in Holmberg et al. (2010). Further, different business purposes and various working tasks in a company need to be supported with different IS and ICTs.

It is, therefore, important for any business to have a proper connection with IS and ICTs strategies (Ward & Peppard, 2002). The historical development of the IS and ICTs in organisations has gradually grown and emphasised their different aspects (Pearlson & Saunders, 2009; Peppard & Ward, 2004; Ward & Peppard, 2002). The authors classify them as different eras in the three-era model such as the DP era during the '60s, management information systems (MIS) era during the '70–80s, strategic information systems (SIS) era during the '90s, and currently the fourth era, i.e. IS capability era, which is characterised by the consideration of organisational resources, skills and knowledge of the employees as well as their experience. There are many challenges with the implementation of organisational knowledge-driven approaches, however, the Web 2.0 technologies facilitate this approach with their social media technologies (Alavi & Leidner, 2001). Companies should try to move to the next era until they reach the last of the eras in order to be able to use the ICTs in an optimal way (Peppard & Ward, 2004). The developments of the various IS and ICTs are to be thoroughly investigated in the domain of CM and Maintenance, especially the e-maintenance since it is necessary to know the current state of affairs when it comes to the use of the latest IS and ICTs in the domain of interest. This is also crucial to find out if the developments and the use of the ICTs are heading towards the IS capability era, which will evince high productivity, efficiency and in general higher organisational performance (Craig, 2008; Ward & Peppard, 2002). In Section 2, the author presents the implemented models, namely the three-era-model and the fourth era model, named the IS capability. All the papers in the review represent and analyse the above-mentioned models. The evolution of the ICTs and their practical use by various companies and organisations is represented at an academic level in the area of CM and maintenance, especially the e-maintenance. The literature findings can be observed in Sections 3–6 and in each section there is a conclusion at the end, where various aspects are highlighted as concerns the models used. In Section 7, there is a discussion and finally a conclusion section.

2. The three-era and IS capability models

The terms IS, IT and ICTs are explained further on, since it is important to differentiate between them in the context of this work. The UK Academia of Information System provides the following definition of IS: "IS are the means by which people and organisations utilise technologies to gather, process, store, use and disseminate information" (www.ukais.org). It is also pinpointed that the Information and Communication Technologies (ICTs) provide greater spectrum of possibilities to process and transfer data and information through the IT. Therefore, the ICT and IT are similar in this context, especially for the purposes of IS. In other words, ICT is an enabler for IS, that focuses on technology rather than on the interception of technology and users within a system, which is the case of IS. The IT and the ICTs provide the infrastructure for intra- and inter-organisational IS.

2.1. The three-era model

One of the models used to organise the findings is the three-era model, which was briefly mentioned in the introduction. The three-era model, which has been proposed by Ward and Peppard (2002), i.e. an extension of Galliers and Somogyi (1987), provides useful aspects available where the pattern of conclusions can be drawn. The first era is the DP era, the second is the MIS era and the third is the SIS era. The fourth era, i.e. IS capability, focuses on sustainability value creation supported by the IS and ICTs.

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Three distinct eras can be singled out, although overlapping, which go back to the '60s (Peppard & Ward, 2004). The period when the DP was widely used is acknowledged to be during the '60s, for the MIS from the '70s to the '80s and for the SIS approximately between the '80s and the '90s. The current IS capability era started at the end of the '90s and the beginning of '00s. The main objective of using the IS and ICTs was different in distinct eras. For the DP, for instance, the main objective is to improve operational efficiency by the automation of the information-based processes. The MIS's key objective is to increase the management effectiveness by providing the relevant information for their decision-making. The SIS's main objective is to increase competitiveness by changing the nature of conducting business, i.e. IS and ICTs investments are the adequate ones required for the specific business strategy of the company and its various departments for the purpose of higher competitiveness. Thus, various aspects of different eras are highlighted in Table 1, such as the nature of technology, the nature of operations, different issues in system development, the reasons for using the technology and finally the characteristics of the systems.

In addition, Table 1 is modified and the extended version, which incorporates the fourth era, i.e. IS capabilities era aspects, is included into Table 1 and is further discussed in this section as well as in Section 2.2. In Table 1 (the column of the DP era) it is shown that the nature of technology lies within the emphasis on computers to improve operational efficiency that is fragmented and has hardware limitation. Most of the technologies used in the DP era are remote from users and controlled by DP itself. The issues in system development are with the emphasis on technical aspects, such as programming and project management, while the reasons for using the technology normally aim at reducing the costs and are technology driven. This era is characterised by automated information-based processes that help to improve operational efficiency focusing on the internal processes.

The nature of the technology for the MIS era encompasses distributed processes that are interconnected where limitation of software programmes may exist for various purposes of decision support. Most of the operations are regulated by the management to satisfy information-based equipment for decision-making. The issues in the system development refer to the support of a business user's needs and the reasons for using the technology are to support business decision-making, i.e. manager and user in their decision-making process. The main characteristics of the systems concern taking control of different processes.

Table 1. The three-era model and its various aspects (modified and extended from Ward & Peppard, 2002)

Aspects	DP era	MSI era	SIS era	IS capability
Nature of the technology	Computers →	Distributed processes →	Networks →	Service Oriented Architectures
	Fragmented →	Interconnected →	Integrated people/Vision →	Flexible/integration
	Hardware limitation →	Software limitation →	limitation →	
Nature of operations	Remote from users controlled by DP →	Regulated by management services →	Available and supportive to users →	Based on collaborative, cooperative aspects, and learning aspects
Issues in system development	Technical issues (programming/project management) →	Support business user needs (information management) →	Relate to business strategy? →	Resource based, information and knowledge-driven aspects
Reasons for using the technology	Reducing costs (administrative) (Technology driven) →	Supporting the business manager (user driven) →	Enabling the business? (business driven) →	Enabling business, while supporting the Is competencies (Resource as well as Information/knowledge/ driven)
Characteristics of the systems	Regimented/ Operational (internal) →	Accommodating/ Control →	Flexible/ Strategic? (external) →	Service oriented/considering the specific needs as well as the holistic picture of the org.

The SIS era uses network technology that is integrated and contains people as well as vision in their objectives when developing the systems, therefore, people and vision limitation can exist in the developed software. The nature of the operations is that they are available and supportive to the users. The issues in system development lie within the objective of the IS to match the business strategy, i.e. to support the needs of the business strategy with the correct IS and ICTs. The reason for using the technology is to enable business, i.e. business-driven approach. In addition, the systems are characterised by being flexible and should be connected to the strategy; therefore, external factors should also be considered when these are developed such as the external business and external ICTs environment, as well as the internal.

The nature of the technology in the IS capability era is characterised by service-oriented ICT practices that are flexible and integrated and consider the organisational aspects as well as users' needs. The nature of the operations is based on cooperation and learning aspects, while the issues in the system development emphasise resources such as the user in the system as well as information and knowledge-driven aspects. The reasons for using the technology are for purposes of enabling business as well as supporting the organisation. The characteristics of the systems are service-oriented considering the specific needs of various employees as well as the entire enterprise interests. In conclusion, different aspects and objectives of the DP, MIS and SIS are a subset of the IS capability and therefore should be implemented to increase a company's competitive advantage.

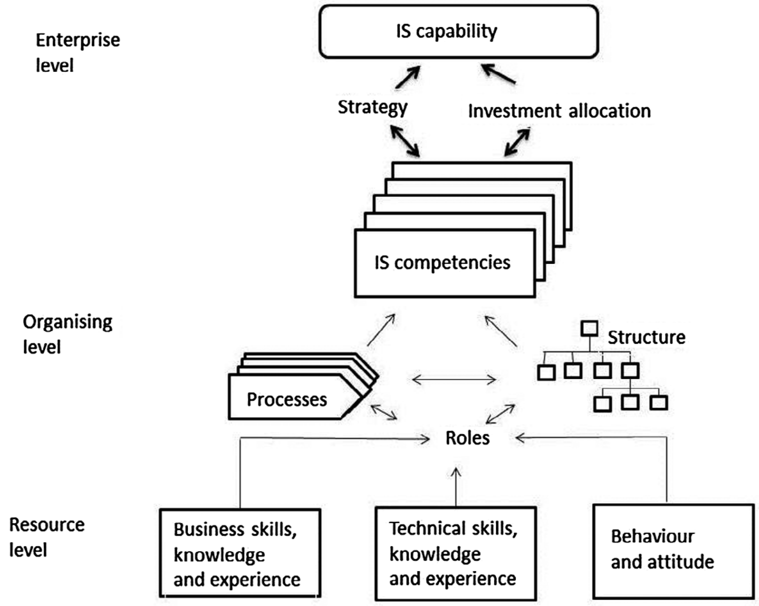
2.2. The IS capability

The IS capability has been highlighted in several works such as Caldeira and Dhillon (2010), Wade and Hulland (2004), Peppard and Ward (2004), Bassellier, Reich, and Benbasat (2001), Bharadwaj (2000), Bharadwaj, Sambamurthy, and Zmud (1999), Feeny and Willcocks (1998a), Ross, Beath, and Goodhue (1996), Lee, Trauth, and Farwell (1995), Sambamurthy and Zmud (1994). The IS capability developed by Ward and Peppard (2002) and Peppard and Ward (2004) is based on the work of Bharadwaj (2000), which emphasises the importance of the resources of a company in connection with the resource-based theory (RBT), which is illustrated in Figure 1.

The IS Capability is characterised by such aspects as the alignment of IS and ICTs with business strategies, while taking into consideration the resources of the organisation, namely the knowledge of the employees (business and technical skills, knowledge and experience) and their behaviour and attitudes. The knowledge of the employees affects in its turn the performance of various processes in which they are involved. Therefore, it is important to take into account all the above mentioned, which as expected will increase the organisational performance. There are some key words to learn to be able to understand the IS capability era and these are the IS competencies, IS capabilities and the RBT. For the RBT there are many definitions such as "collection of human and physical resources bound together in an administrative framework, the boundaries of which are determined by the area of administrative coordination and authoritative communication" (Penrose, 1959), while Hamel and Prahalad (1994) refer to a company as an organisation with a "portfolio of competencies".

Therefore, the IS competencies and IS capabilities, which are part of the RBT, can be influenced by the resources they have. In conclusion, the competencies mean the ability of a company to organise and use its various resources, i.e. a company's capacity to deploy their resources. The capability is about how the organisation strategically is able to use those resources to accomplish its company's goals stated in its strategy. Nine IS competencies are identified and these are the IS/IT leadership, business system thinking, relationship building, architecture planning, making technology work, informed buying, contract facilitation, contract monitoring and vendor development (Feeny & Leslie P., 1998b). Meanwhile, Peppard, Lambert, and Edwards (2000) identify six domains of IS competence, i.e. Strategy, the IS contribution, the IS capability, exploitation and solutions delivery and supply. These six domains of IS competencies are in their turn composed of 26 IS competencies. The six domains and the 26 IS competencies involve a framework for positioning the IS competencies. What can be learned from this framework is that when those competencies are known, it is when a company is able to distribute its IS and ICTs in a successful way. The model that explains the fourth era,

Figure 1. A model of the IS capability (modified from Peppard & Ward, 2004).



i.e. the IS capability, can be seen in Figure 1. It has three levels, namely the resource level, the organising level and the enterprise level (Peppard & Ward, 2004).

In Figure 1, the resource level means the resource components are important for the IS competencies. When it concerns handling the IS and ICTs, it involves resources such as skills, knowledge and behavioural factors of employees as well as external factors. The organising level focuses on how these resources are taken care of through various processes, structures and roles to create IS competencies. The IS capabilities differ for all companies, since some companies have strong IS capability and can deliver IS and ICTs that affect their business leading to competitive advantage and some not. Then it is concluded with the help of the model that the value of the IS and ICTs is not completely technical, though various activities within different processes are handled with the support of the IS and ICTs. The sustainability of any organisation's ability to deliver value from their IS and ICTs investment is to understand how their business domain works. It is, therefore, crucial to understand what contributes towards the developments of the aspects that are involved in affecting the sustainability of the IS and ICTs, which results in competitive advantage when the activities and various processes are supported by the IS and ICTs. Consequently, the IS capability era consists of all the former eras, but incorporates new aspects mentioned, for instance, the resource level, organisation level as well as the enterprise aspects. The classification of the literature findings corresponding to the adequate era is based on different aspects from the three-era model (see Table 1) as well as the characteristics of the IS capability illustrated in Figure 1.

In this paper, the author has tried to elicit from various literature findings diverse aspects of different eras and then matched these findings with the suitable era. The survey of relevant literature has been conducted with the following keywords in different combinations: Internet, Intranet, Web technologies, CM and maintenance, ICTs, e-maintenance. The search has been done in different databases, such as the Emerald's, Inspec, ACM, IEEE Xplore and Google scholar during the years 2000 to 2014. Thereafter, the relevant papers have been chosen and studied. The aim of the research was to reveal published work done in the area of CM and maintenance supported with the ICTs as well as to determine where in the historical development of the IS and ICTs is the domain of CM and maintenance, especially e-maintenance, i.e. in the DP era, MIS era, SIS era or the IS capability era. These findings are presented in Sections 3–6 and in each chapter there is a conclusion at the end, where various aspects are highlighted with respect to the models used. In Section 7 there is a discussion and in Section 8 future challenges and issues are addressed. Finally, in the last section a conclusion is presented.

3. The DP era

In this section, the literature findings are presented and discussed since they are considered to be a vital part of the DP era. The new multi-agent architecture for the monitoring of Flexible Manufacturing Systems (FMS) is suggested (Ouelhadj, Hanachi, & Bouzouia, 2000). The application is made with Java technology JESS (Java Expert System Shell) and the agent communication is done with TCP/IP (Transmission Control Protocol/Internet Protocol). The agent system consists of different modules, such as knowledge (specific for each agent), control (with decision-making capabilities), cooperation and communication (where the ability of the agent to cooperate and communicate existed).

Taking into account the ideas of Mangina, McArthur, and McDonald (2000), the description of the architecture for CM based on intelligent agent technology is presented. This three-layer architecture is called COMMAS (Condition Monitoring Multi-Agent System). Design and functionality of the diverse agents and also the key issues involved in multi-agent systems (MAS) are discussed. Groups of different kinds of agents are proposed for different functions in the architecture. COMMAS was initially developed and applied to monitor the gas turbine start-up sequence. Conceptual framework, analysis and design including the information flow among the agents, and the implementation of COMMAS are described. The system has three kinds of application agents, namely: Attribute Reasoning Agents, Cross Sensor Corroboration Agents and Meta-Knowledge Reasoning Agents, clustered in three different layers. In addition, it has interface agents. Initially the system was built using JATLite but ZEUS was evaluated as well (Mangina, McArthur, & McDonald, 2001a). Later, the system was built using the ZEUS Agent Building Toolkit (Mangina, McArthur, & McDonald, 2001b). The agents use modal logic for internal reasoning within the theoretical approach of BDI model. The use of modal logic is expounded in another paper (Mangina, McArthur, & McDonald, 2001c). Further on, COMMAS is applied to the identification of partial discharge signals emanating from defects in extra high voltage gas insulated switchgear (GIS) at the substations (Mangina, McArthur, McDonald, & Moyes, 2001d). Partial discharge can be caused by various kinds of defects. This system is called COMMAS GIS and described in detail. Moreover, the study has been carried out on the model. Referring to the work of Judd, McArthur, McDonald, and Farish (2002), one should be aware of the fact that the researcher describes a MAS based four-layer-architecture for the CM of the power transformers by using ultra high frequency of partial discharge (UHFoPD) as a monitoring parameter. Consequently, the layers are the following: data monitoring, interpretation, corroboration and information layer. Each layer contains a group of agents for a specific task.

A new approach based on a multi-agent system and a transformer equivalent heat circuit thermal model is presented (Feng, Buse, Wu, & Fitch, 2002). It is meant for the on-site monitoring of the distributed transformers in a power grid. The purpose of the thermal model is to make temperature predictions. It can predict transformer winding, cooling, and oil in-let and out-let temperatures. It helps engineers understand the working conditions of the transformers. It also carries out the transformer load ability analysis and it helps engineers simulate the possible conditions before they switch the loads between the transformers. The model has been successfully implemented at one substation. However, the ambition is to monitor hundreds of substations that are widely distributed geographically simultaneously. There comes the role of a multi-agent system. A variety of agents cooperate to provide on-line real-time CM and diagnosis of the transformers. The users also have access to the data through Internet or Intranet. The mobile agent software was applied to power system and circuit breaker maintenance tasks (Kezunovic, Xu, & Won, 2002). It is felt that the currently used preventive maintenance and emerging condition-based maintenance strategies need flexible information processing technique and software architecture. Various potential application scenarios have been described and the relevant software features have been discussed. They believe that agent technology meets the requirements to be applied in maintenance because of its characteristics of the optimal network bandwidth usage, integration capabilities of heterogeneous data and security. The development of the two types of hardware is also presented, namely Network

Computing Unit (NCU) and Network Computing Terminal (NCT) (Ishihara, Shirota, Sekiguchi, Sato, & Sawai, 2002). They believe that these two technologies in conjunction with Internet and Intranet technologies can increase the efficiency in operation and maintenance through protection and control of equipment. The software architectures of NCU and NCT consist of a data management system, a server platform, a communication platform, a security system and an agent platform. They go through such applications for the system as the power quality and security monitoring, fault location and fault analysis, operation and maintenance of power utilities. They also mention that the Web-based fault location system that utilises Intranet technology with real-time information processing provided excellent results. Other applications which are mentioned briefly are power equipment monitoring system and the possibility of applying a remote operation and monitoring mobile system through the use of a Web Server and mobile agents.

The use of Internet for a Web maintenance portal is described by Wollschlaeger and Bangermann (2003). Two implementation examples for a Web maintenance portal are illustrated. The authors say that the Internet technologies are flexible and have great potential. But the only problem they see is to choose the right technology so that it can be utilised as efficiently as possible. The first implementation is the e-maintenance portal for machines where all business logic lies on the server side. The advantage it gives is that all pages can be accessed through a standard Web browser and also by smaller mobile devices, such as personal digital assistants (PDAs). It also gives good security restrictions because all source codes lie on the server and are invisible on the client machines. The requirement that the application should be run on a standard Web Server made the Hypertext Preprocessor (PHP) script be a good alternative. The reason is that PHP is available for Windows and Unix platforms and it supports XML files. The second is the maintenance Portal for PROFIBUS PA Systems for process control systems. The authors emphasise the importance of integration of similar systems independently into the network structure and network gateways, respectively. The technology used to transport data is Hypertext Transfer Protocol. HTML is used to access different objects and it has also support for XML files, which the authors see as indispensable for this kind of implementation. It should be highlighted that in his research, Kunze (2003) goes through certain Internet and Intranet characteristics for power plants. He mentions that conventional diagnostics systems are tightly connected to each other. While in Web-based diagnostics systems there is a tendency to keep the software modules independent and let them function autonomously. It gives the advantage of connecting the already existing diagnostics systems to the overall Web. The requirement of technology needed to achieve this is a server, structured software design, interfaces between the software modules, i.e. databases where data are stored. The author believes that little money is needed to invest and to implement Web technology in the maintenance sector and that the possibilities are more than the investment needed. The most expensive part of Web monitoring and diagnosis is the user interfaces. The key steps of a methodology are to develop a MAS based architecture for diagnostics and CM applications in power industry, which is considered as worthwhile paying attention to (McArthur, Hossack, & Jahn, 2003). This approach was utilised while designing and developing the Protection Engineering Diagnostic Agents (PEDA) system and its operation is explained. The COMMAS of Judd has been modified to add two more agents in the interpretation layer (Judd et al., 2002). Buse, Feng, and Wu (2003) describe a system that uses mobile agents and a multi-agent system to provide data analysis facilities in a power system environment with view of implementing data retrieval, remote analysis and reporting functions for data stored in power substation databases. A model of the mobile agent for this application is derived, and a number of experimental results regarding the relative performance of mobile agents and static client server agents are presented. The results suggest that when low bandwidth of the network is used, mobile agents have the potential to greatly increase the performance of this application. The latency effect is also almost eliminated. The mobile agent for remote access to a number of monitoring and control devices is proposed. Buse and Wu (2004) report more results from the experiments mentioned earlier (Buse et al., 2003). The experiments are conducted at a low network bandwidth (1Mbit/s) and at various network latencies as well as a number of interactions. It is found that for low number of interactions, or where latency is low, the client-server or static agent method is superior. But when the number of interactions and the latency is large, mobile agent takes less time than the static agent. It is reported that the use of mobile agents shows appreciable performance improvement over static agent (client server) for latency between 25 and 100 ms when more than 30–40 interactions are performed in a sequence once a mobile agent is launched. The paper conjectures that it is so because the time taken by the mobile agent to locate the server, move and connect to the relay was large in proportion to the total time. The static agent has only to connect the relay and hence the start-up time is much less. The paper, therefore, suggests that to make mobile agents more efficient for a small number of interactions, certain efforts should be made to reduce this preparation time.

If to speak about Xue, Chengliang, and Lee (2004), it is worth mentioning that the authors emphasise the need for developing smart maintenance and Web-enabled remote monitoring device interface and system technologies based on GEM (Generic Equipment Model). They describe the technical architecture of Web-enabled monitoring systems (www.imscenter.net). The backbone of such a platform is the use of GEM@WORK. It is a tool for the creation of flexible Web-enabled data access applications on different control mode functionality. The wireless online continuous monitoring of temperature with the help of switchgear at a power plant has been executed for two years and is described by Livshitz, Chudnovsky, and Bukengolts (2004). They mentioned that the temperature profiles followed load faithfully, even the minor change in current. After a month of installation the monitoring system detected high temperature. It was, however, due to insufficient cooling in the switchgear room. Therefore, sufficient ventilation brought it down. An unresolved issue, which appeared one year after the installation, has also been reported. The authors talk of a Web-based system and software developed for monitoring the power quality and show how this technology can be used for wireless online continuous temperature monitoring. Catterson and McArthur (2004) describe the transformation of the off-line COMMAS of Judd et al. (2002) to an on-line one. In doing so more agents have been added to the system. In addition, the paper discusses the practical problems faced and the solutions found. McArthur, Strachan, and Jahn (2004) validated the on-line COMMAS using a laboratory set up where a defect was created in the transformer and UHFoPD was monitored. The work done by Bunch et al. (2004) describes the architecture of a multi-agent system to monitor the condition of complex chemical processes as well as flexibly and appropriately informs all the plant personnel if and when an off-normal condition arises on their preferred devices with an appropriate level of urgency to attend. The authors call the architecture KARMEN (KAoS Reactive Monitoring and Event Notification).

Tiba and Capretz (2006) in their turn present a conceptual multi-agent system architecture with diagnosis and monitoring capabilities. The architecture called SIGMA is illustrated through the Gaia methodology and designed by Agent Unified Modelling Language (AUML). A prototype built with JADE 3.3 tested in a nuclear power plant simulation shows the architecture validity. Zhao, Zhao, Tan, and Yan (2006) use multi-agent system to monitor oil condition and fault diagnosis. The multi-agent system is based on case-based reasoning for the purpose of DP and fault analysis. McArthur, Davidson, and Catterson (2006) review Agent Communication Languages (ACLs) and mention that PEDA and COMMAS have been developed based on FIPA-ACL standards. The reason to use the FIPA-ACL was because it is a stable standard in comparison to others, such as KIF, RDF or CCL, that still are in an experimental phase. The authors believe that if FIPA standards were followed to develop agents, then the interoperability between agent systems from different sources would increase, as well as the integration of agents with already existing non-agent systems. The paper goes through the matter of integrating PEDA and COMMAS systems. They believe that this could be done through the creation of an upper ontology for power engineering applications. The upper ontology would facilitate the integration because it would contain basic concepts of the domain that PEDA and COMMAS or other ontology applications could use. The common representation of concepts would reduce the complexity of ontology mapping, i.e. all power engineering applications would use the same basic common concepts, for example transformer, conducting equipment and how they are related. The authors mention various development methodologies and illustrate MAS methodology that was used during the development of the PEDA system. The methodology consists of six phases, including requirement and knowledge capture, task decomposition, ontology design, agent modelling, agent interaction modelling and specification of agent behaviour. The drawback of the agent methodologies is that they are not fully matured and the existing ones have not still been applied to many applications, i.e. it has not been verified whether they are suitable for all kinds of development projects. The authors believe that the technology used is crucial because it decides how the agents will communicate, but none of the existing methodologies takes this matter into consideration in the development phase. Therefore, when developing autonomous agent, the agent anatomies are crucial and none of the agent methodologies raises this question in their different phases either. Though, this is important because it provides the agents with levels of reactivity, pro-activeness and social ability. The paper goes through tools for developing MAS where the authors argue that JADE is the most popular tool for building agent systems for power engineering applications. Campos and Prakash (2006a) discuss the development and various attempts to standardise CM and maintenance through the use of various AI, DAI and MAS technologies. They present the historical development of agent-based architectures for CM and maintenance as well as the already existing agent communication technologies.

Wiliem, Yarlagadda, and Zhou (2006) describe development of an internet-based real-time water CM system prototype based on Web technology (DataSocket, ActiveX) and software (LabVIEW and VB) for the communication via the Internet. The variables monitored are temperature, turbidity, pH-value, dissolved oxygen and electrical conductivity. Such authors as, for instance, Zhou, Chen, Wang, and Yao (2008) provide a solution which combines both embedded and Web technologies for the purposes of equipment CM. The CM and maintenance together with remote access is done through the use of network and Web browser. The communication security is also worthwhile paying attention to in their work. The applications have been tested with successful results and it has been shown that it can diminish the system running costs as well as alter the efficiency of maintenance work task.

3.1. Analysis

Table 2 summarises the findings that hinge on the three-era model. *The nature of the technologies* in the above-presented work is in general based on agent technologies, multi-agent systems (MAS), Web technologies, such as the HTML, XML, Data Socket, ActiveX and Java technology. In addition to them, JATLite and Zeus Agent Building Toolkit are widely used. Other software applied was Lab VIEW. Moreover, such kinds of hardware as NCU and NCT together with Internet technologies are vastly incorporated since it is believed that they can increase the efficiency in operation and maintenance through protection and control of equipment. The mobile agents are used and compared with client-server technologies to evaluate the speed of data and information sent through the network. The authors conclude that the mobile agents are more efficient when small numbers of interactions are made. Moreover, there are works that highlight the possibilities of the Web technologies that provide the access to various client machines, namely the PDA; however, no

Table 2. Characteristics of the data processing era

Aspects	DP era
Nature of the technology	Agent technologies, multi-agent systems (MAS), Web technologies, such as the HTML, XML, Data Socket, ActiveX, Java technology, JATLite and Zeus Agent Building Toolkit
Nature of operations	Remote from the users, emphasis on different technological problems and solutions
Issues in system development	The amount of layers for different solutions, BDI approach for the agent systems development, modal logic design steps for the internal reasoning within agents, ontology methodology an extension of the UML called the Agent Unified Modelling Language (AUML) with special characteristics for the agent systems
Reasons for using the technology	In general for condition monitoring and maintenance
Characteristics of the systems	Regimented/operational and for the internal processes

application has been developed for this purpose so far. *The nature of operations* from the abovementioned findings is characterised as being remote from the users and lays an emphasis on different technological problems and solutions. *The issues in the field of system development,* which have already been discussed, are the amount of layers for different solutions, which differs for the software applications developed. The BDI approach is suggested when agent systems are being developed. It is a modal logic design steps for the internal reasoning within agents. Other findings used the ontology methodology consisting of the following six phases: the requirement and knowledge capture, task decomposition, ontology design, agent modelling, agent interaction modelling and specification of agent behaviour. In addition, there exists an extension of the UML called the AUML with special characteristics for the agent systems. The applications suggested and developed in this section are heavily technology driven; therefore, the system development, modelling and design are not much illustrated since it is believed that a prototype approach is normally used when applications are made. *The reasons for using the technology* are technical solutions it brings and, in general, for CM and maintenance, i.e. plan when it is time to provide service to the equipment with the support of diagnostics, smart maintenance and Web-enabled remote monitoring, online continuous monitoring of temperature of switchgear at a power plant, CM of the gas turbine start-up sequences, CM of the power transformers, on-site monitoring of the distributed transformers in a power grid, power system and circuit breaker maintenance tasks, diagnostics and CM of applications in power industry, the provision of data retrieval, remote analysis and reporting functions for data stored in power substation databases and for the monitoring of FMS. In addition, another purpose is real-time water CM system where the monitored parameters are the temperature, turbidity, pH-value, dissolved oxygen and electrical conductivity. *The characteristics of the systems* are that they are regimented as well as operational and serve for the internal processes. Finally, it should be taken into account that all the papers have an emphasis on the technical aspects of the ICTs.

4. The MIS era

In this section, the literature findings under discussion are acknowledged to be the part of the MIS era. Waclawiak, McGranaghan, and Sabin (2001) describe the implementation of an Intranet-based monitoring system to track the performance of distributed power substations. The important benefits realised are power quality and reliability, prioritising system improvements and identifying problem conditions. Sun, Yang, and Huang (2002) outline a multi-agent architecture that handles distributed systems for chemical process monitoring and diagnostics. Each agent is composed of a control modular, a database, a communication block, a knowledge base, an information processor, a data acquisition and network listen block. The knowledge interchange between the agents is made through automatic translation languages of messages programmed in CKRL (common knowledge representation language) that is based on C++ programming language.

Marzi and John (2002) define the design and the experience with the running of the prototype of a competence promoting system developed on the basis of a multi-agent architecture and also an instrument to measure competence enhancement. The authors call it ComPASS. As a knowledge-based decision-support system, its main objective is to support the operators of CNC machine tools in fault finding. Fu, Ye, Cheng, Liu, and Iung (2002) suggest an Intelligent Control-Maintenance-Management System (ICMMS) to analyse the equipment of an automation system based on a multi-agent system (MAS) approach. ICMMS architecture consists of agent blocks, such as the perception block, monitoring & diagnosing block, planning block, intention block, actions block and knowledge base. All the agents have similar structure though the only thing that varies is their behaviour and knowledge. These agents accomplish different tasks and cooperate with one another to achieve a common goal. The intercommunication among the agents is done with ACL based on FIPA (Foundation for Intelligent Physical Agents).

Hung, Chen, Ho, and Cheng (2003) present an e-Diagnostics/Maintenance framework for the semiconductor factories, which is based on Web technologies, including the Web Services, XML signature and XML encryption where security is considered. The system is designed with the object-oriented approach where the UML is used to model the application. They go through different components of the application and the steps involved in its development. Rao, Zubair, and Rao (2003) pinpoint two models for CM using Internet technology, viz.; on-site and off-site expert systems. Then they describe in detail an on-site expert system that they have developed. They mention that Internet technology is different from other remote accesses because there is no need for special software. The only thing required is a browser, i.e. user interface that integrates different systems. They see the potential new utilities of this technology, i.e. the way machines can be maintained continuously online at different geographical locations or checked through the Internet for any failures that may occur.

Naedele, Sager, and Frei (2004) suggest the use of MAS for the asset management in the manufacturing plants. The authors propose a 5-layer architecture that they have shown to be ISO 13374 compatible, namely the data acquisition, diagnostics, correction, meta-control and human machine interface layers. The aim is to support the information flow from bottom to top. The communication between the agents is done through an ACL proposed by FIPA. The MAS architecture takes into consideration the conflicting goals that exist in a plant maintenance department and production department. The proposed aim of the agents is to act as a plant asset management decision-maker. The scenario could vary, for instance one such like scenario is when the maintenance department wants a machine for inspection/maintenance before it fails but the production department wants high utilisation of the equipment and hence does not hand over machine to the maintenance people. Here is where the multi-agent system comes into picture as a problem solver through the negotiation of relevant agents with the objective to achieve the most optimal solution and hence meet the requirements of an enterprise. Zhang, Zhang, Luo, Zhao, and Wong (2004) dwell upon an extension of the traditional Maintenance and Diagnostic Systems (MDS) for this purpose within the framework. The authors mention that there is a need to incorporate prognostics into the CM to provide early warnings and take preventive actions against any possible failures which can escalate. Thus, a knowledge discovery technique is used and tested to form the prognostic knowledge into the system as well as to test new algorithms. Ren, Luqing, and Chuang (2004) state that the cooperation among different departments in an enterprise and between experts in their respective domain knowledge at different geographical locations is of great importance. To achieve this in a most effective way, they see the need to utilise new information and communication technologies, such as MAS. The paper proposes the principle and three-layer architecture of a remote maintenance support and management system based on MAS. A prototype has been developed and applied successfully to a water level control system for remote decision support.

Hung, Cheng, and Yeh (2005) propose Web Services based on e-diagnostics framework (WSDF) in accordance with the functional requirements of e-diagnostics systems, International SEMATECH (ISMT). It supports the integration of automated processes and diagnostic information for semiconductor equipment. The developed WSDF is designed with ICTs, such as Web Services, eXtensible Markup Language (XML), Simple Object Access Protocol. The use of these technologies facilitates the integration of diagnostic information over the Internet and provides support for functions needed for e-diagnostics, such as automatic collection of equipment data, remote diagnosis, monitoring the equipment, and the analysis and prognosis of equipment performance. In addition, there is the integration and exchange of various data supported by different databases and systems as well as the interoperability of cross-platform and distributed systems. The authors propose as well the procedure for the development of the WSDF consisting of five stages, i.e. system analysis, e-diagnostics framework design, component design and implementation, application construction, system integration and testing.

Zu, Liu, and Xu (2006) propose an ontology based on heterogeneous information management cooperation architecture for decision support and CM data. The authors go through the ontology definition and knowledge structure, as well as the distributed physical and logical layers. The logical architecture consists of information source layer, logical data schematic layer, semantic integration layer and application layer. The aim of the four layer logical architecture is to semantically integrate utilities information resources for knowledge management and application cooperation. They mention a global ontology management system (GOMS) and semantic Web Services techniques.

Lee, Ni, Djurdjanovic, Qiu, and Liao (2006) illustrate a Watchdog agent that works in an e-maintenance environment for the assessment and prediction of a machine or process performance. The agent has the capability to answer questions, such as when an equipment or process may fail/degrade to an unacceptable level. Another question the embedded system answers is why the equipment or process has degraded. The authors mention that the embedded system has been validated through various case studies that are presented in their work. These case studies are rolling bearing performance prediction, industrial network fault detection and maintenance scheduling. They discuss also different ways on how to increase the usability of the tools, namely performance forecasting and a decision-making module to enable optimal maintenance decisions. They believe that a successful implementation of the embedded watchdog agent would lead to about zero downtime performance of equipment and manufacturing systems.

Bahga and Madisetti (2012) present a cloud-based framework for the storage, processing and analysis of huge amount of machine maintenance data collected from various sensors in different industrial machines and systems, such as gas turbine plants, wind turbine farms, nuclear power plants and smart grids. The papers refer to the architecture, design and implementation of the so-called CloudView and in what manner the suggested cloud-based framework works. Moreover, the framework involves business logic based on the case-based reasoning (CBR) approach for different machines fault prediction. The authors mention that the use of the Cloud computing eases the gathering of sensor data and the creation of case-base with global information, i.e. data from a large amount of machines, which are gathered at a central site and for further analysis and fault diagnosis. The authors mention that the so-called global approach is a concept that is realised when the entire sensor data are collected in the cloud and the business logic based on CBR is performed in the cloud. In the suggested architecture it was shown that it was possible to perform successfully the fault predictions in real time in the cloud.

Kour, Karim, and Parida (2013) use cloud-based computing technology for the information logistics for purposes of railway systems which need data from different sources, such as railway maintenance, railway operation and railway business data with the aim of making correct diagnostics and prognostics decisions. The suggested e-maintenance Cloud Architecture is based on Net technologies, for instance the e-maintenance railway cloud is implemented through the use of Asp.Net and SQL server 2012. Kour, Karim, Parida, and Kumar (2014a) suggest the use of the e-maintenance solutions together with the Cloud computing and RFID technology. The data acquisition is done with the use of the RFID, which facilitates the data collection. The gathered data is later sent to the e-maintenance Cloud computing where it is processed and later used for analysis and decision-making for the purpose of maintenance planning. The authors Kour, Tretten, and Karim (2014b) show how the e-maintenance approach is used with the support of the Cloud computing for the railway sector for purposes of CM and maintenance. The suggested e-maintenance solution is built with the aim of effective maintenance decision-making and consists of an on-line data acquisition, which collects the data remotely with the upkeep of the Cloud computing.

4.1. Analysis

Table 3 summarises the findings based on the three-era model. *The nature of the technology* is revealed via multi-agent systems (MAS), embedded and Internet technologies, RFID as well as Cloud computing. In addition, there are applications developed with automatic translation languages of messages programmed in CKRL (Common Knowledge Representation Language), which is based on C++ programming language for the communication between intelligent agents as well as mobile agents systems. The ACL proposed by FIPA (Foundation of Intelligent Agents) is used also for the same purposes as the earlier mentioned work. The findings show that *the nature of the operations* is mainly for the CM and maintenance management purposes. *The issues in system development* are supposed to provide information for the maintenance engineer and for decision support. *The*

Table 3. Characteristics of the MIS era

Aspects	MSI era
Nature of the technology	Multi-agent systems (MAS), embedded and Internet technologies, RFID, Cloud computing, CKRL (Common Knowledge Representation Language), ACL (Agent Communication Language)
Nature of operations	Condition monitoring and maintenance management purposes
Issues in system development	Information for the maintenance staff and for decision support
Reasons for using the technology	Monitoring and diagnosis, monitor the performance of distributed power substations, decision support of electric utilities, asset management in the manufacturing plants, support the operators of CNC machine tools in fault finding, to analyse the equipment, rolling bearing performance prediction, railway maintenance decisions and tools, maintenance scheduling
Characteristics of the systems	Control purposes and assist for decision support

reasons for using the technology are various, such as to handle distributed systems for chemical process monitoring and diagnosis, asset management in the manufacturing plants, Web technologies to monitor the performance of distributed power substations, for decision support of electric utilities based on the condition-based assets management approach, to support the operators of CNC machine tools in fault finding, to analyse the equipment of an automation system based on a multi-agent system approach, rolling bearing performance prediction, industrial network fault detection and maintenance scheduling, railway maintenance decisions and tools, including performance forecasting and a decision-making module to enable optimal maintenance decisions. In general, it can be concluded that *the characteristics of the systems* presented above serve for decision support and control purposes.

5. The SIS era

In this section, the literature findings are evaluated to be part of the SIS era presented in the discourse below. A framework is illustrated for Web enabled e-maintenance systems (Lee, 2001). The author goes through the framework and the hierarchy of the intelligent e-maintenance system that consists of three levels of intelligence. According to the authors, the first level, i.e. product, machine and process level should emphasise predictive intelligent functions. It is so because there is a need for better understanding of different factors involved in the degradation of equipment and product. It is mentioned that a watchdog agent could serve to inform of any deviation from predetermined values and forewarn the maintenance staff about the impending failure. The second level, that is the system level, consists of software and client-server applications. The integration of the production machines is done through Internet or Intranet where a server machine can be connected to any database with a common protocol, taking away the need for a central database. The Web Server contains formatted Hypertext Mark-up Language (HTML) and the client machines have the applets that in frequent intervals request data from the Web Server. Finally, the enterprise level consists of three elements for asset optimisation and management system. The elements are used for monitoring, prediction, transformation (information for diagnostics and decision-making) and synchronisation functions (the required integration with e-business systems).

Hossack, Menal, McArthur, and McDonald (2003) propose to use the multi-agent system for a flexible and scalable alternative to current approach of many standalone systems' integration for post-fault disturbance diagnostics in a power system. The scholar demonstrates the application of PEDA to disturbance diagnostics by using actual power system data. According to Szymanski et al. (2003) internet technology should be applied to the integration of the maintenance processes in a project called PROTEUS. The objective of the project is to enhance the maintenance process efficiently by bringing the expertise to the user via the Internet. They propose to use extensively powerful data structuring technologies, such as XML (Extensible Markup Language), application integration techniques and Internet related technologies. The overall economic objective is proposed to be achieved by reducing the time for diagnostics and repair, and prevent the failures by CM the field equipment. According to the authors, efficient implementation of preventive maintenance management strategy has three fundamental requirements. These are: continuous assessment of equipment health, maintenance and repair of operation process management and comprehensive data presentation and synthesis. Consequently, successful implementation of the functions mentioned above results in a fully integrated platform.

Speaking about Lee (2003), the author goes though the characteristics of the Internet technology. Internet can facilitate the integration of all the flows from supplier to customer using communication protocols, such as TCP/IP (Transmission Control Protocol/Internet Protocol) and wireless and predictive technologies. He believes that e-manufacturing provides the plant floor assets and asset management with abilities to monitor and predict performance losses. Other characteristics of e-manufacturing are the possibilities of rescheduling production and maintenance operations. The integration of different systems and applications is also possible. The tools to be used for the purpose of e-manufacturing are data and information transformation, prediction, optimisation and synchronisation tools. Data and information transformation or data mining tools are for data reduction, representation and prediction. Prediction tools are to detect degradation, performance loss or trend of failure. Optimisation tools compare the performance of the machine in its different states. Finally, the synchronisation tools are utilised to integrate such e-systems as Customer Relationship Models (CRM), Business-to-Business (B2B), e-commerce and Enterprise Resource Planning (ERP). The paper also reports the development of a Watchdog Agent for the machine degradation assessment.

Yu, Iung, and Panetto (2003) describe a Problem-Oriented Multi-Agent based E-Service System (POMAESS) for e-maintenance. The prototype has two types of agents, i.e. a Negotiation agent and an Expert agent. The Expert agent has the expertise of a problem domain, as the production management expert, the maintenance expert, and the control expert, and works in conjunction with the Negotiation agent to give an opinion on the problem. The Negotiation agent controls the negotiation and draws conclusions as an inference engine. The agents collaborate with each other via their built-in knowledge to achieve a common goal. The goals of industrial POMAESS are economic, performance, reliability and availability. To achieve this they believe that such parameters as cost, reliability, availability, maintainability and productivity need to be optimised. Other objective of the POMAESS is to provide the agent with the infrastructure to "interconnect" different agents (reactive and cognitive) in the architecture. Djurdjanovic, Lee, and Ni (2003) suggest the use of agent software, called Watchdog Agent in conjunction with CBM concept. The Watchdog agent provides information about the following types of performance: performance assessment, performance prediction and performance diagnostics. The decision-making advice and conclusions are based on historical data, engineering knowledge and different engineering models.

The paper of Catterson, Davidson, and McArthur (2005) goes through the discussion of integration of PEDA and COMMAS in detail. The idea behind the integration of the system is to enhance the level of decision-making support. They believe that the integration could be done through a common upper ontology for power engineering applications where common basic concepts are used between the two MAS systems. McArthur, Catterson, and McDonald (2005) describe an architecture and methodology to integrate all the CM and asset management functions for a transmission and distributed network-using COMMAS. The key steps in the methodology are the following: requirements capture/knowledge capture, task decomposition, ontology design, agent modelling, agent interaction modelling and agent behaviour functions. Having worked with COMMAS over the years, the researchers have come to the conclusion that no single intelligent technique produces right diagnostic results. So more and more intelligent agents with complementing abilities to diagnose have been added and the corroboration agent, which combines them in a way that the disputes are correctly resolved, has been suggested.

Bangemann et al. (2006) illustrate an architecture with the purpose to provide an integration platform when applying maintenance, i.e. its main objective is focused on the infrastructure to achieve integration rather than develop tools for maintenance. The results are based on the project PROTEUS. The platform provides an optimal use of Web technology, such as Web services to access various systems for CM equipment and maintenance. The use of Web services allows the platform to achieve three requirements, namely heterogeneity, extensibility and coherence. McArthur and Catterson (2005) show how the function of the COMMAS in the laboratory can be used to accommodate more than one CM techniques and equipment at different locations. Campos and Prakash (2005) proposed a MAS based 3-layer architecture for the same purpose. Han and Yang (2006) suggest an e-maintenance system that consists of two subsystems: maintenance centre and local maintenance. The maintenance centre function is divided into four groups: the fundamental research group, enterprise group, expert group and industry case history collection group. The local maintenance function does internal maintenance, such as CM. Three important processes are mentioned in the local maintenance function subsystem. These are: the continuous assessment of equipment health, maintenance and repair operation process management, comprehensive data presentation and synthesis. The main idea with the two subsystems is coordination, co-operation, share of information and negotiation through the Web technology. The proposed system has been successfully applied to an induction motor. The authors believe that the e-maintenance system can provide the efficient reduction in the maintenance costs and solve the problem of lack of experts.

Wu, Chen, Li, and Li (2006) propose a Web-based multilayer distributed software architecture. The architecture is a remote monitoring and diagnostic system, i.e. Web-based Remote Monitoring and Fault Diagnostic System (WRMFDS). The authors go through the design and development of the WRMFDS for key equipment in petrochemical and metallurgical industries, called VSN-NetMDS. However, the authors opine that the system is valuable for any plant following CM and maintenance. The design of the whole system is done with Unified Modelling Language (UML). They illustrate the architecture of the VSN-NetMDS that consists of a combination of hardware and software systems that connect different expert systems through the Internet. The architecture (VSN-NetMDS) hinges on the distributed software technology. The component framework of VSN-NetMDS is done based on Microsoft's COM (Component Object Model). It consists of five-layers according to Microsoft layer strategy and meets the requirements of integrating legacy into Data Acquisition Systems (DASs). The layers are the database service layer, the data access layer, the control logic layer, the presentation layer and finally the drive service layer. Microsoft's COM has been chosen to conquer many problems, such as reusability, complexity of large scale projects, i.e. complexity of relations among objects and the difficulty of encapsulation. The architecture (VSN-NetMDS) consists of a VSN-NetRDS and a remote diagnostic centre with such functions as user management, remote analysis, remote diagnosis and component library. It consists of VSN-NetEMC enterprise monitoring centres with such functions as user management, remote monitoring, fault diagnostics and equipment management. The architecture has also many VSN-NetDAU that are data acquisition units with the following functions: data acquisition, DP, online alarm and data backup, which are connected to the various enterprise monitoring centres and authorised experts and users.

The authors, Xiao-Feng, Yu-Jiong, and Kun (2008) discuss and design an intelligent maintenance decision support system, called intelligent maintenance decision support system (IMDSS), for a power plant. They present the system design, i.e. system functions and the platform. The IMDSS consists of a database, database management system, model base, Model Base Management System, knowledge base, Knowledge Base Management System, Reasoning Machine, Control Panel of System and its interface. The platform is based on Internet technologies by the use of windows server, Microsoft SQL server. Its goal is to assist a maintenance engineer in his various working tasks. The system follows a CBM strategy. It is believed that the implementation of the software system will result in reduced costs, provide reliability and as a result lead to competitive advantages.

Table 4. Characteristics of the SIS era

Aspects	SIS era
Nature of the technology	Multi Agent Systems (MAS), Web technologies such as Web Services, XML, HTML. MAS, Web technologies, such as the Web Services, XML, HTML and intelligent techniques
Nature of operations	Solution for the asset management, the preventive maintenance and for CBM strategies
Issues in system development	Different asset management strategies, such as the CMB
Reasons for using the technology	Integration of systems and maintenance processes, asset management functions, engineering applications, integration of standalone systems for post-fault disturbance diagnostics in power systems. Intelligent systems that follows the CBM strategy
Characteristics of the systems	CBM, and should in this way be connected to the business strategy of the company

5.1. Analysis

Table 4 summarises the findings based on the three-era model. *The nature of the technologies* is presented and analysed in this section, taking into account the MAS, Web technologies, such as the Web Services, XML, HTML and intelligent techniques. In addition, there are the communication protocols, such as TCP/IP (Transmission Control Protocol/Internet Protocol), wireless and predictive technologies used. Moreover, the Internet and intranet solutions are used for integration purposes which with the help of a server machine can be connected to any database with a common protocol, taking away the need for a central database. *The nature of operations* serves a good solution for the asset management, the preventive maintenance and for CBM strategies. *The issues in system development* are the relation to different strategies, such as the CMB. *The reasons for using the technology* lie in the integration of systems as well as maintenance processes, asset management functions, the use of engineering applications, and the integration of standalone systems for post-fault disturbance diagnostics in power systems. Other findings uncover the reason for the development of an intelligent maintenance decision support system, which follows the CBM strategy. One of the authors talks about the e-manufacturing approach, where integration is not only done via maintenance, but also on the so-called e-Systems, including Customer Relationship Models (CRM), Business-to-Business (B2B), e-commerce and Enterprise Resource Planning (ERP). CBM concept is also supported via MAS. In addition, the concept of e-maintenance and its ICTs as well as the framework for Web enabled e-maintenance systems are applied. Another framework is presented for the integration of distributed measurement and control systems. Moreover, the coordination, co-operation, share of information and negotiation supported by Web technologies are mentioned in the work. Finally, *the characteristics of the systems* are based on strategic approaches, such as the CBM, and should in this way be connected to the business strategy of the company.

6. The IS capability

The papers acknowledged to be the integral part of the IS capability era are illustrated below. The work of Zhang, Halang, and Diedrich (2003) emphasises the importance of integration of data and industrial systems that do supervisory control or management or both. They mention that there are a few technologies to choose from for the integration of data and systems. These technologies are Web services, CORBA, Net (of Microsoft) and DCOM. However, the authors see more advantages of the maintenance through the implementation of the Internet and agent technologies. These advantages are gained from the wide acceptance of the Internet among enterprises around the world and the agent system provides the realisation of intelligence and co-operative features for the automation systems used in industry. A platform is designed so it can support the agent technologies and information flow in e-maintenance. The aim of the platform is not only to support data or services integration but also to enhance the knowledge management in an enterprise (e.g. through the integration of already existing knowledge bases and expert systems and the suggested agent systems).

The multi-agent-based platform for e-maintenance supports the combination of such technologies as XML, Web Services and knowledge base systems. The FIPA (Foundation for intelligent physical agents) agent registering mechanism and JADE programming language are used. Web technology is used to integrate the systems within an enterprise and at an inter-enterprise level.

Wang, Tse, and Lee (2007) describe a remote fault diagnostic system based on Web technologies and mobile devices, i.e. mobile phone and a PDA. The solution provides the managers and engineers with the possibilities to acquire the results of the machine diagnosis with the help of the mobile devices anywhere. The authors go through the ICT system architecture comprising the data acquisition and processing, the diagnosis data publishing, and the client side. The XML is used to transfer data through the architecture. The software application part that takes care of the diagnosis is developed by the use of LabVIEW. The analysis of the condition of the equipment is not made on the Smartphone or PDA. Instead of the usual approach, this was done on a Personal computer (PC). Arnaiz, Gilabert, Jantunen, and Adgar (2009) present in their paper an integrated maintenance platform named DYNAWeb, which is an ICT architecture that consists of Web technologies, such as the Web services developed in a project called DYNAMITE (Dynamic decisions in maintenance). The architecture is based on the e-maintenance concept and follows the CBM strategy where the OSA-CBM architecture is used. The developed systems are tested with on or off-line services with the use of client machines, such as the mobile devices. A predictive maintenance system is also presented. Campos, Jantunen, and Prakash (2007, 2009) present a mobile solution, i.e. PDA for mobile e-maintenance based on embedded and Web technologies. The PDA was tested for CM especially with the simulated signal of a faulty rolling element bearing. A mobile Computerised Maintenance Management System (CMMS) was also tested with, for example, a work management system. The system was based on the e-maintenance concept and followed the OSA-CBM architecture. The system provides the maintenance engineer with the possibilities to perform his work task at the shop floor and to interact, i.e. communicate and collaborate, with experts at the diagnostic centre whenever it is needed. Iung et al. (2009) discuss the current state of the e-maintenance research as well as the future research directions in the area. The e-maintenance concept is briefly analysed and in their viewpoint is connected with such principles as pro-activity, Web Services or the Internet, knowledge, intelligence and collaboration. They present the first conceptual e-Maintenance framework based on 5 abstraction levels and on the Enterprise Architecture (EA), based on the Zachman Framework. The abstraction levels are the e-maintenance strategic vision (business and goal) that support the “scope”, the e-maintenance business processes that support the Business View, the e-maintenance organisation that supports the Architect’s view and the e-maintenance IT infrastructure supporting the builder’s view. In addition, as expressed in Zachman’s framework, the following points are highlighted for each step, i.e. Data, Function, People, Network, Time and Motivation. Further on, they present a complete e-maintenance platform, i.e. TELeMAintenance platform (TELMA). Finally, they see a number of important common industrial and academic research directions and one of these is that the e-maintenance platform must be based on collaboration and cooperation capacities to support well new services.

Cao and Jiang (2008) develop an Intelligent Equipment Maintenance Decision (IIEMD) platform based on Service Oriented Architecture (SOA) to support collaborative maintenance decision and remote equipment diagnosis. They mention that the lack of inter-operating among plant software systems can be solved through the research on e-maintenance systems. The illustrated architecture IIEMD is an ontology-supported hybrid system that hinges on reasoning logic, rule-based reasoning (RBR) and case-based reasoning (CBR) techniques for equipment maintenance decisions. The suggested SOA can perform data presentation and synthesis as well as a continuous assessment of equipment health and is a support for maintenance repair decisions. In addition, the SOA facilitates the integration of other systems for more comprehensive decision-making. The key technologies in the system are, for instance, the inference processes and ontology-based knowledge base. The system is planned to be extended with other decision support techniques, such as a neural network and support vector machine that will be integrated. Karim, Kajko-Mattsson, and Söderholm (2008) explore the Service Oriented Architecture (SOA) within the e-maintenance as well as provide an eMaintenance platform (eMP) with the aim to serve as an effective tool for organisations to perform their maintenance and support. The authors mention that the SOA is being accepted worldwide, since it promises agility, mobility, interoperability and reuse. Another factor is that it better aligns with business objectives. The proposed eMP consists of three levels, i.e. Specification, Design and Implementation. The first level (Specification) has all the information that is needed to perform maintenance. The second level, i.e. Design level, identifies such design components as the Content Services, which implement logic for the interaction between different data sources. The Interface Services design services that handle and adapt to other devices, such as a portable handheld computers. The Miscellaneous Service has the responsibility to design services that cover the business logic. The third level, i.e. implementation level realises the SOA components into the required Web Services and business logic for the specific situation. The authors mention that a prototype of the eMP has been developed with Microsoft Net framework and Microsoft SQL server 2005 with the intention to validate it in conjunction with industry.

Karim, Söderholm, and Candell (2009) describe a taxonomy issue for an eMaintenance Management Framework (eMMF) based on service-oriented approach. They conduct the study based on a case study of aircraft maintenance within a process view where certain aspects of maintenance information and ICT applications are described. The eMMF consists of two parts, i.e. the eMaintenance Management Model (eMMM) and the eMaintenance Platform (eMP). The eMMF involves the roles, processes, repositories to handle the eMP. Meanwhile, the eMP is an SOA application applied with the aim to provide users with data for decision-making. They conduct an interesting discussion about the information logistics place within the e-maintenance approach as well as ICTs to be used for an optimal solution. For instance, they mention that the maintenance processes aim to sustain the capability of an asset to provide it with the service and thereby achieve customer satisfaction, which requires the provision of the right information to the right information consumer, i.e. user, with the right quality of data and information at the right time. Moreover, the desired situation can be achieved through the appropriate information logistics, which makes the right information available at the right time and the right place. Continuously, they say that the e-maintenance concepts have various interpretations depending on the researchers, however, what is common is that a vital part incorporates the application of ICT to achieve information logistics within the maintenance area, i.e. the e-maintenance requires an appropriate ICT architecture, which can be manifold. They mention that the use of Web Services as well as the Service Oriented Architectures (SOA) is considered to be an attractive approach. Other authors that discuss the SOA within the e-maintenance approach are Cannata, Karnouskos, and Taisch (2010) they investigate the benefits of the use of a SOA-based platform to integrate business and shop floor level, through Web Services technologies. The authors present and highlight how future industrial system environments based on SOA platforms such as the SOCRADES can be of support for the e-maintenance applications.

Capella et al. (2012) suggest the architecture for e-maintenance consisting of two domains, i.e. the floor-shop and the cloud domain. In the floor-shop domain, a mobile device is suggested to be used through a tether-free process interface. It is suggested to implement a Cloud domain since it provides the means to support maintenance via Internet connection. The suggested mobile device can be connected to both the floor-shop and the cloud domain. They mention that the proposed architecture, which combines the mobile devices, Cloud computing and Internet connectivity, supports the maintenance engineer in his different work tasks by compensating for the lack of expertise, minimising the expert technician dependency resulting in reduced maintenance task time. Their results show the following positive aspects: the possibility to reduce the economic requirements through the use of the suggested architecture supported by a Cloud resulting in higher availability and productivity of the manufacturing plant. Another work within the e-maintenance approach, where it is suggested to support mobile devices with Cloud computing, can be found in Sharda (2012). The author suggests the Cloud computing since it can provide services that are not available in their own domain. The author mentions also a new concept called i-maintenance, which stands for integrated, intelligent and immediate maintenance.

Guo, Gu, Liu, Wang, and Zhao (2010) underline the importance of cooperative maintenance decisions based on swarm knowledge, i.e. based on multi-knowledge, multi-method, multi-resource and multi-information. The authors explain Swarm's knowledge as the collective behaviour of individuals, who interact with their environment, and by doing so create coherent global functional patterns. It involves individuals that are open to each other and share information through a knowledge grid, i.e. a framework that provides the possibilities to share geographically and organisationally distributed heterogeneous resources, such as information, knowledge and even software. The authors present the architecture of intelligent knowledge grid based on a service platform. It gives, for example, service and scheduling information for various power plants. Its objective is to enhance the decision-making process, make an accurate diagnosis, reduce maintenance costs and improve the efficiency of the diagnosis treatment. Their further research is searching technology, negotiation strategy and scheduling problems for the knowledge services. Karray, Chebel-Morello, Lang, and Zerhouni (2011) frame a new concept that has emerged, i.e. S-maintenance (Self-maintenance), which requires new services, such as intelligent maintenance and self-maintenance. It is based on new generation of maintenance systems founded on knowledge-based systems that involve learning aspects. They mention that current maintenance systems do not have these characteristics. This development comes, therefore, as an evolution of the maintenance systems, which extends the e-maintenance concept from an integration tool to the core of the maintenance process. The authors propose a type of architecture based on s-maintenance. The s-maintenance system consists of an information system and a knowledge management system, which is a core part of the system having an inference engine and a knowledge base. They mention that the s-maintenance system should have a high level of knowledge acquisition, i.e. supported by self-learning and tracking, elicitation, reasoning and re-use. The authors propose a component-based architecture where the core of the architecture involves the following four software layers: coordinator, mediator, human interface manager and knowledge base manager.

Jantunen et al. (2010a) developed an e-maintenance platform named DynaWeb consisting of a number of solutions for CM. They mention that the emergent ICTs provide the maintenance engineer with possibilities to access whatever information he needs wherever he is as well as to report different work tasks at place. Essential ICTs for optimised utilisation of the suggested DynaWeb application is the use of the Mimosa and its layered Web Services, which are based on information flow according to OSA-CBM distribution. The e-maintenance solution was tested with successful results at three industrial sites. However, one of the main constraints was the integration with the already existing systems legacy tools, since they are not developed based on international standards. Consequently, this highlights important issues that need to be considered when implementing an e-maintenance system, because the integration between data and systems is the key aspect for successful implementation of industrial e-maintenance systems. Jantunen, Giordamlis, Adgar, and Emmanouilidis (2010b) present the services and software application intended to be used in mobile devices in e-maintenance within the same platform mentioned earlier, i.e. DynaWeb platform. They discuss the role of the mobile device in the domain as well as the associated hardware, the development of suitable software and the customisation and integration of adequate wireless networking solutions. In addition, they go through typical PDA, i.e. personal digital assistant, usage scenarios in maintenance operations. Moreover, the wireless communication, technical requirements, the limitations of current technologies as well as the mobile user interfaces are defined. Campos and Jantunen (2011) discuss the use of the Semantic Web and Web 2.0 technologies for the e-maintenance applications. They go through various characteristics of the ICTs in e-maintenance, such as the Web Services, Semantic Web and Web 2.0. It is believed that the emergence of the latest Web technologies, for instance the Web 2.0, makes the organisational structure and user, i.e. maintenance engineer, become an important part of the system because of the characteristics of the Web 2.0 technologies. In addition, if the Web 2.0 is implemented in the area of CM and Maintenance, i.e. in the e-maintenance applications, then it will become an important tool to handle the knowledge, i.e. their expertise and experience of various users. Consequently, they mention that in the case of a maintenance engineer carrying a mobile device while performing his various work tasks, it will facilitate the knowledge sharing between the employees. Further on, a platform based on Web 2.0

technologies would enable the maintenance expert to generate content, collaborate, communicate and publish information and knowledge via a bottom-up approach. Consequently, access to various kinds of information and knowledge would be facilitated for the user whenever it is needed. In addition, the authors mention that the social media technologies support even a learning environment, which is necessary in the domain owing to the fact that different work tasks that an engineer performs can be complex and require a comprehensive and deep knowledge. Therefore, the social media support tools with the incorporated learning aspects become convenient to be used in the domain. Emmanouilidis, Jantunen, Gilabert, and Starr (2011) go through the e-maintenance enabling factors, e-maintenance services as well as the use of mobile devices. They mention that the e-maintenance approach has emerged as a powerful technological framework. Its implementation with its characteristics, such as integration, promises more efficient maintenance management. In addition, they mention the need for training and knowledge management, since the users, i.e. the maintenance management professionals, need to master different competencies. Therefore, the author believes that the Web 2.0 and social tools will aid a company with the organisational knowledge management process. They talk about a maintenance knowledge management ecosystem, based on Web 2.0 technologies, which would support the maintenance professionals with, for instance, virtual working spaces, which is important for the knowledge management process and supports the development of collective intelligence.

Pistofidis, Emmaouilidis, Kopulamas, Karampatzakis, and Papathanassiou (2012) consider the e-maintenance as an approach that provides a comprehensive framework for efficient Engineering Asset Management. Consequently, the authors present a layered architecture for e-maintenance, which they define as WelCOM (Wireless sensors networks for Engineering asset Life Cycle Optimal Management). The developed architecture is validated in an industrial piloting test case, in the manufacturing industry. The suggested architecture is a multi-tier design and includes a few functional blocks. The system parts of the architecture are, for instance, CMMS or machinery components that can connect their own operations to the WelCOM components. The architecture consists of five subsystems and interfaces. The first subsystem represents the overall system data model. The second subsystem consists of processing, access and administration components. The third one is a scalable knowledge management system, which engages in reasoning for fault diagnosis, prognosis and maintenance support. The fourth one supports the users' access to the platform functionality. Finally, the last one involves an e-training environment that supports the employees in their learning about the system, its functionality (e.g. technical documentation and content) at place with portable devices. Papathanasiou, Emmanouilidis, Pistofidis, and Karampatzakis (2012) talk about the integration of an e-learning module and e-support that supply the maintenance engineer with the desired applications through the mobile devices. The modules that the e-support consists of are CM, which includes videos, manuals or technical reports. The proposed application considers the characteristics of a mobile environment, i.e. the networking capabilities and the mobile user interface. The proposed WelCOM e-Learning and e-support components are designed for the maintenance engineer working in a plant. The authors mention that the main benefits of the WelCOM platform are accurate, fast and can be seen through clear work, ordered assignment and context and depend on training support and low-cost integration with e-Maintenance systems. Pistofidis and Emmanouilidis (2012) discuss within the same platform architecture, i.e. WelCOM, the context semantics aspects for an IT infrastructure that supports engineering asset management as well as maintenance practice and planning. Further on, the authors underline the benefits of the Wireless CM and the use of the mobile devices in the domain. Chebel-Morelloa et al. (2012) develop an intelligent application based on knowledge management for industrial diagnosis and repair maintenance. The platform, which is an e-maintenance platform, provides distinct collaboration possibilities. The platform consists of software components and software services for maintenance support, which enables the maintenance engineers to communicate with one another when needed as well as access the necessary information. The system is developed to be tested in a mini solar station to perform, for instance, diagnosis and prognosis of the pumping system of a Photovoltaic system to show the feasibility of the approach. The photovoltaic water pumping systems (PVPS) consist of a photovoltaic array, a pumping subsystem and a water tank. The e-maintenance supported by the ICT approach is beneficial for the equipment in question, since it provides support from a remote expert to a technician at place.

6.1. Analysis

Table 5 summarises various findings based on the three-era model. *The nature of the technologies* mentioned by the authors in this section incorporates the Web technologies, such as the Service Oriented Architectures (SOA), Web Services, XML and MAS as well as Cloud computing. In addition, there are CORBA, Net (of Microsoft) and DCOM used as well as JADE and FIPA. *The nature of operations* consists of the e-learning, collaboration, cooperation and resource allocation. In addition, the maintenance processes are mentioned together with the information logistics due to such characteristics as the right information transferred to the right user with the right quality and at the right time. *The issues in system development* are related, as mentioned before, to e-learning, collaboration, cooperation and knowledge management as well as the sharing of knowledge, resource management, and consequently information logistics approaches are discussed. *The reason for using the technology* is the e-maintenance approach, e-learning module and e-support of the maintenance engineer. Other reasons mentioned by certain authors are the need for an evolution or further development of the e-maintenance approach considering such aspects as intelligent maintenance, self-maintenance, i.e. a new generation of maintenance systems founded on a knowledge-driven approach. Other authors mention the need for further research on technology, negotiation strategy, and scheduling problems of various knowledge services. In addition, there is a growing trend to use the mobile technologies in order to provide information and knowledge to the maintenance engineer whenever it is needed in any format adequate for the situation. Different platforms are as well suggested for various purposes of e-maintenance as well as information and knowledge needs. Moreover, not only the need for integration of various systems for more comprehensive decisions is mentioned, but also the importance of enhancing resources is underlined, i.e. the knowledge of the employees in an enterprise by the integration of information and knowledge in various standalone systems, namely databases, knowledge base and expert systems. *The characteristics of the systems* are in general resource-driven, i.e. knowledge-driven and organisational aspects are highlighted in those systems in connection with the ICTs, the CBM and e-maintenance approach. In addition, Services Oriented Architectures (SOA) and Web Services are mentioned, which gives many opportunities and options to integrate various systems. Finally, the use of the mobile devices provides the maintenance engineer with the right information and knowledge where and when it is needed.

Table 5. Characteristics of the IS capability era

Aspects	IS capability
Nature of the technology	Web technologies, Service Oriented Architectures (SOA), Web Services, XML, MAS, Cloud computing. In addition, CORBA, Net (of Microsoft), DCOM, JADE and FIPA
Nature of operations	e-learning, collaboration, cooperation, resource allocation, etc.
Issues in system development	Issues connected to e-learning, collaboration, cooperation, knowledge management, knowledge sharing, resource management and information logistics
Reasons for using the technology	e-maintenance approach, e-learning module, e-support of the maintenance engineer, intelligent maintenance, systems based on knowledge-driven approach
Characteristics of the systems	The systems are resource driven, i.e. knowledge- and organisational-driven aspects are highlighted. The systems are connected to the ICTs and the CBM and e-maintenance approach

7. Discussion

7.1. The three-era

The findings show that researchers are working on ICTs, which are part of the DP. They are testing new software technologies, such as the intelligent and the mobile agents, as well as mobile systems for CM and Maintenance purposes. Other applications found were intelligent agents for the objective of negotiation between agents with different communication languages. In addition, the mobile agents are compared with the client server technologies for data and information flow, including performance improvement for data retrieval. The Web technologies are tested, respectively, in this era for DP. The findings mainly concentrate on the technical aspects of the solutions. Therefore, the characteristics of the DP era are crucial to consider when developing its various ICTs for the domain of interest, since the area of CM and Maintenance is a data intensive domain and might lead to heavy load on the databases or servers as well as to sending data and information to various client machines. The technological developments are in their nature dynamic, and it is, therefore, important to understand the new ICTs and their characteristics to be able to use them in an adequate manner. It has been shown, for instance, that the need for a common or centralised database is not a need for the integration of data, since the latest ICTs, i.e. Web technologies, especially the Web Services (WS), provide the integration of not only data but also information and distributed software systems, i.e. WS and web methods are the interoperability, shareability and reusability ensured in an organisation. Moreover, recently there have also emerged concepts and technologies, such as the cloud computing, which have brought new dimensions to the maintenance department where the ICTs' functions and the companies' resources can be managed outside the companies' domain.

The solutions in the era of MIS provide the maintenance worker with the possibilities of diagnosis, analysis and prognosis of different assets. The proposed Information System (IS) involves such solutions as, for instance, Knowledge-based decision support systems, Intelligent Control-Maintenance-Management System (ICMMS), Expert Systems, Multi-Agent System (MAS) for the asset management. When it concerns the SIS era, the software solutions are connected with the CBM strategy and few findings mention the e-business, the overall business strategy or/and the production department strategy, which should be considered when developing CM and Maintenance solutions.

7.2. IS capability

Continuously, it has been found out recently that the entrance into the fourth era, i.e. IS capability era, is at the rudimentary stage in the domain of CM and Maintenance, where the researchers are beginning to mention, discuss and even test applications which correspond on the whole to the aspects of the IS capability. There are few isolated applications, i.e. modules that are being developed, which fit into this era where researchers mention that there is need of other aspects to be considered. In general, there are findings that can be part of the IS capability era based on the e-maintenance approach. The e-maintenance is a concept which brings the following factors: the importance of the strategies and even aspects, such as e-collaboration, e-cooperation and organisational e-learning as part of the ICT solutions. The mobile devices, such as PDA, have started to be used, which facilitates the knowledge sharing among the employees, such as the maintenance engineer working with his various work tasks at the plant floor, where the maintenance engineer can communicate with the expert at the diagnostic centre. The use of mobile devices increases the resource level impact on the organisation as well as facilitates collaboration, cooperation and learning. By doing so, the maintenance department is moving into the next era, i.e. IS capability, since all aspects are considered, namely the resource level, organisation level as well as the enterprise level. Everything mentioned above goes in conjunction with one of the grand challenges for manufacturing industry mentioned in Iung et al. (2009), i.e. the instantaneous transformation of information gathered from a vast array of diverse sources into useful knowledge from making effective decisions. The e-maintenance is a contributor to reaching the IS capability. Consequently, there is a growing need for a more comprehensive approach that not only emphasises on the integration, but considers the other aspects in the IS capability as well as sustainability of the ICTs in the area of CM and Maintenance. Moreover, the support that the e-maintenance brings into leading the company into the IS capability era depends much on the definition of e-maintenance concept that the researchers use in their ICTs developments, since it can be a definition where the emphasis is on the integration of data, information and systems. However, to support the IS capability, as mentioned before, it requires a more comprehensive approach, where the resource level, organisation level and enterprise level are considered when developing various ICTs of the maintenance department. In addition, the three-era model and/or the IS capability model can be perceived as a maturity model on how the companies use the IS and ICT, since depending on their usage they might be in different stages of it. In the last mentioned eras, including MIS era, SIS era and IS capability, we can still find aspects of the former eras, such as the DP era. They are all interconnected with each other and are in a real industrial situation because if a specific company is moving into a later era, it does not mean that one should ignore the former era's aspects in their solutions since they support the next era's various aspects. It is, however, important to learn that it is not the ICTs that bring benefits, but the way these technologies are implemented and how well they are connected to the company's goals and objectives, i.e. the ability to support the overall strategy that matters.

7.3. IS capability and Web 2.0 technologies

The open source solutions also bring new possibilities and issues when it concerns the developments of software applications for CM and Maintenance, as well as e-maintenance solutions. It is, therefore, important to understand these ICT developments to be able to use them in the most appropriate manner, while considering their characteristics in the various IS and ICT solutions, since they might take the company into the next era, i.e. the IS capability, which should be the aim of any company because it gives the possibilities to use the ICTs in an optimal manner for the benefit of the whole company. In any case, the presented findings and ICT developments go hand in hand with the vision of Peppard and Ward (2004), which is illustrated in this paper with the help of the three-era model and the newly emerged fourth era, i.e. IS capability. This is a natural development, since the three-era model highlights the fact that companies should be in the latest era to be able to use the ICTs efficiently. In addition, it concords with the recent developments of the Web technologies, such as the Web 2.0, i.e. the social media technologies, which provide new possibilities for the use of the ICTs for the purposes of collaboration, e-cooperation and e-learning in the e-maintenance platform. Therefore, it should be expected in the future that the use of the Web technologies, such as the Web 2.0 and its social media technologies, will increase to provide possibilities for collaboration, e-cooperation and organisational learning, i.e. knowledge-driven approach, where consideration is taken to the organisation, resources and overall business strategy. The Web 2.0 and its social media technologies will increase because it is natural that companies want to move to the last era to be able to use the ICTs optimally for organisational purposes and one should take into account the fact that these ICTs emphasise and facilitate the aspects that are part of the IS capability. Consequently, there is a need of a thorough research in the domain of interest to understand the implications of the social media technologies in the e-maintenance. The authors Campos and Jantunen (2011) and Emmanouilidis et al. (2011) highlight important aspects that the implementation of the Web 2.0, i.e. the social media technologies, can bring. For instance, the use of tags can simplify searching functions because the tags facilitate search for information by using one word descriptions added to the search field. The field then provides a few alternatives in a search situation where the maintenance engineer wearing a mobile device can select the most appropriate word for the specific search. In addition, the RSS can notify users about changes or updates in the system. Even so-called authoring (which enables seeing, for example, who made the latest changes or updates of the system) can facilitate the creation and updating of the content. The Web 2.0 technologies, such as, for example, Wiki' and RSS, offer other possibilities due to the fact that the content can be created by all employees in the company and not only by the programmers and employees responsible for the Intranet of a company.

The social media technologies work as a collaborative tool and the Web as the Web platform, which allows the maintenance employees, in this case, to share information, knowledge and experience via a bottom-up approach. This implies a trusted (confidential) environment, i.e. that the information and knowledge that is shared is trustworthy, since it all works in a self-organised manner, such as the Wiki concept, where the shared information is expected to be reliable. Consequently, it is important to understand how the emergent technological developments reshape both the role and status of the user (Craig, 2008). The use of the emergent Web technologies and new architectures highlights important paradigm shifts, such as the innovation of processes from a top-down to a bottom-up model. Moreover, other important aspects comprise the value of ownership of data to the end users, i.e. in this case the possibilities of a maintenance engineer working in the plant floor to share his knowledge with other employees with the support of the social media technologies.

7.4. IS capability, IS methodologies and the Web 2.0 technologies

When it comes to the development of these software applications, it is crucial to consider which IS methodology should be used, since the emergent Web technologies, namely the Web 2.0 technologies, have led to a new situation, and there is no standard for its development. For example, the Web 2.0 produces a wealth of data, however its semantics is poor resulting in integration difficulties. Further, the Semantic Web solves the integration issues, but suffers from users who lack the corresponding knowledge to use. Nevertheless, what becomes crucial if the social media technologies become a fact in the domain is to understand how to elicit from the huge amount of unstructured data the useful information that provides knowledge, i.e. decision support to the users, for instance, in how to perform a work task in an optimal manner. Consequently, there are, therefore, IS methodological factors to consider to the integration of the data and information that is created by those Web technologies, as well as user aspects. The Web 2.0 provides flexible organisational learning tools where the employees support each other in a learning environment. If these Web technologies are applied in e-maintenance, the utilisation of ICTs in the domain will be more in line with the existing state of the art solutions, which in many cases has already been tested and used in other domains.

There is a need in e-maintenance for research to understand how the social media technologies can be used and how they can support their maintenance processes. It should be executed especially in the case when the mobile devices are used, since the mobile devices and the emergent Web technologies and consequently together provide the engineer with the needed information anytime anywhere as well as with collaborative and learning aspects in their daily work, which thoroughly innovates various practices in their different work tasks. In addition, in a Social media technology solution the user becomes an important part of the system, therefore a resource-based perspective as well as knowledge-driven theories, organisation theories and the infological equation by Börje Langefors, among other theories apart from the Scandinavian School of Informatics, become relevant even today. The infological equation emphasises the need to understand the specific users' pre-knowledge when developing the system, especially the user interfaces because information or knowledge depends very much on the user's previous knowledge. It provides the developer of the IS with the complex inter and intra individual aspects of a user. The equation takes into consideration parameters, such as the information (or knowledge) produced from certain data and the interpretation process of each user. Hence, what is information or knowledge from a specific data presented in a user interface depends greatly on the specific user (Dahlbom, 1995), therefore, it is believed that it is important to consider the learning and knowledge-driven approaches when developing IS, which are to be part of the IS capability era. In connection to this, it is important to determine if the already existing e-maintenance applications and systems are providing the users, in this case the maintenance engineer, with the relevant data, information and even knowledge to perform their various work tasks.

7.5. Standardisation

Other important issue to consider is the standardisation process because it increases the speed of acceptance of the emergent IS and ICTs as well as, in this case, acceptance of the mobile devices in the domain of interest. The issues to take into account in the standardisation process are many. However, as it is highlighted by Lyytinen and King (2006) and Markus, Steinfield, Wigand, and Minton (2006), they have become ubiquitous, heterogeneous, networked and complex. Consequently, the standardisation of the IS and ICTs involves many aspects, including users, vendors and software development organisations. It is, therefore, of significant importance to conduct comprehensive research approach as well as projects where all important parties/stakeholders are involved or where all the interests are highlighted to concretise the standardisation, which in its turn, as mentioned earlier, increases the acceptance and efficiency of the IS and ICTs. In the case when it concerns the use of the mobile devices together with the emergent Web technologies, what matters is which data and information should be accessed via a mobile device. In addition, when it comes to the IS and ICTs it is crucial to understand how the different modules as well as the information between the existent and new modules should take place. The standards should emerge from the needs of doing different activities and processes, for instance when an engineer performs his different work tasks to optimise the use of the IS and ICTs for those processes.

7.6. Cloud computing

Additionally, an interesting emerging phenomenon is the Cloud computing, i.e. network-based computing over Internet, which appeared during the late 2007s. Its main objective is to deliver on demand high quality ICT services containing high reliability, scalability and availability in a distributed environment. Thus, it is important to understand how it could be used in the maintenance department, since numerous positive aspects are promised by its use, such as lower costs, access to immediate hardware resources, lower ICT barriers to innovation, easier access to various services in order to acquire applications which might not have been possible before. In the Cloud computing, the entire network-based computing over the Internet is seen as a service. The Clouds can be categorised as Infrastructure as a Service (Iaas), Platform as a Service (PaaS) and Software as a Service (SaaS). In the domain of interest the main questions would be regarded as how to handle the CM and Maintenance and especially the e-maintenance as a Service (MaaS). The Cloud computing is an emerging phenomenon where initial efforts to understand and test its use in the domain were found and acknowledged to be part of the MIS and IS capability era's characteristics. However, the characteristics of the Cloud computing Services overlap all of the three-era model parts and the IS capability since, for instance, the data gathered and stored from the sensors is part of the DP and is of crucial importance for the e-maintenance. In addition, the choice to use the Cloud is a strategic decision for the maintenance department to be able to match the demand and requirements of the ICTs with the CBM strategy. Consequently, the use of the Cloud computing provides the e-maintenance with all the benefits needed to optimise the organisational performance to be on the cutting edge when it comes to the use of the ICTs at a lesser cost, with high reliability, scalability and availability, as mentioned before. The important aspects of Cloud computing in connection with the resource management of IaaS, including scalability, customisation and reusability as well as the performance metrics, namely delay, bandwidth reliability and security, are discussed in the comprehensive survey paper by Manvi and Krishna Shyam (2014). The security aspects are rather important when the Cloud computing is used since the security strategies that have been developed since the 1980s are not functional for the Cloud computing because the servers' part of the clouds is not in the same domain, i.e. the data owner and Cloud computing servers are normally in two different domains. Consequently, numerous efforts have been made considering this matter and evolving system models and security strategies are being debated and tried, explicit for the system with the features of Cloud computing. These omit, for instance, cryptographic methods and data decryption keys (Tysowski & Hasan, 2011; Yu, Wang, Ren, & Lou, 2010). Nevertheless, the convenience of the Cloud computing assurances increased the use of its Internet-based computing services. Nonetheless, no matter which ICTs or Internet-based computing services are chosen for the maintenance department, it should be done by taking into account their various characteristics in order to use them optimally and avoid possible disadvantages. Consequently, it is vital to investigate how these ICT developments can affect the future e-maintenance applications and different processes in the maintenance departments due to their own specific characteristics, since the services that the Cloud computing offers are extremely useful.

Finally, the domain of interest will reach the IS capability era completely when all the aspects at the resource level, organisational level and enterprise level are considered when developing the IS and ICT applications. It is, therefore, important to consider the use of an IS methodology approach when developing the software applications for the domain that would consider all these aspects, i.e. user, organisation as well as the enterprise level. As stated by Sein, Henfridsson, Purao, Rossi, and Lindgren (2011), there is a need for a research design method that recognises that the IS and ICTs, in this case the mobile devices, emerge from the interaction with the organisational context, even when the initial design is guided by the researcher's intent. It is, therefore, important to examine a multidisciplinary approach to conduct research at the latter era, namely the IS capability one. It is, however, heartening to learn that the area of CM and Maintenance, especially e-maintenance, today can be partly acknowledged to have initiated and be conducting research that is part of the last era, since it promises sustainability in the ICTs used by the industry.

8. Future challenges and issues to be addressed

It has been stated that the use of the three era and IS capability model have facilitated the understanding that to be part of the fourth era, i.e. the IS capability era, there is a need to consider the experience and knowledge of the employees as well as use the ICTs to support this, e.g. to share those data, information, knowledge and experience resources among them. Therefore, companies and organisations reaching the IS capability era will be confronted with new challenges, as mentioned throughout the discussion section, which they will have to address. Consequently, when the new emerging social media technologies, i.e. Web 2.0 technologies, enter into the maintenance department to provide e-maintenance solutions and support the maintenance engineer in his different work tasks, as it has already been stated, it will result in various challenges. For instance, the data produced by the use of the social media technologies is unstructured, i.e. the social media Web 2.0 technologies create a huge amount of unstructured data, therefore it would be crucial to understand how the integration can and should take place so it becomes useful for different maintenance processes when those are supported by the Web 2.0 technologies, namely for collaboration, e-cooperation and organisational learning and knowledge sharing. Moreover, for the most successful use of the social media technologies, there is a need to understand the organisational design and aspects that are needed to support an environment of trust where the employees are able and prepared to share their knowledge. Consequently, the Web 2.0 technologies emphasise and support a learning environment that needs to be addressed by the companies and academia, i.e. how to use this for their specific needs and domain for the interest of the whole enterprise. There has already been done a great deal of research in the area of knowledge management in academia for different domains, and researchers within the domain of e-maintenance should benefit from this and try to understand how this concept and the ICTs can be developed and implemented in the e-maintenance applications. In addition, in the development phases of these Web 2.0 solutions it would be of great importance to understand the information system methodology that is adequate for its design and development, since the web applications have characteristics that differ from regular software, and especially the Social media technologies. It is, therefore, important to understand this phenomenon and develop proper methodologies and modelling techniques for its developments.

Another interesting point is the use of the Big Data Analytics within the Asset MIS, especially for the e-maintenance applications. It is so since their use for both structured and unstructured data could lead to more comprehensive decision-making with the aim of taking different maintenance and management decisions. In addition, the Client server technologies have been a common practice to store and access data within an organisation. However, with the entrance of the Cloud computing we are confronted with a new situation where the organisational data is stored in a system outside the organisation's domain. It is, therefore, the data management and security aspects that become of a crucial importance when data is stored and processed outside the organisation's domain, as is the case when the Cloud computing is used.

Finally, as stated earlier, companies that use the latest ICTs, such as the Web 2.0, will have in their use flexible organisational learning tools where the maintenance engineers, in this case, can support one another in a learning environment. Furthermore, the technological advancements are by their nature dynamic, and it is, therefore, important that the new developments go in hand with the already existing standards to speed up the emergent ICTs acceptance and their further development in the industry. Consequently, if these Web technologies are designed, developed and implemented in e-maintenance, the use of the ICTs in the domain will be in line with the current state of the art solutions, which as previously said, in many cases has already been tested and used in other domains. The obstacles that can be singled out are connected with the development of the ICTs by the industry, which has emphasised the technological aspects of various ICTs while overlooking the characteristics of the context. However, to achieve the IS capability era there is a need to consider the organisational context through the use of a multidisciplinary approach to be able to develop, implement and use the ICT tools in a successful way as stated by, for instance, Sein et al. (2011), where it is emphasised the importance to recognise that an ICT artefact emerges from the interaction with the organisational context even when the initial design is guided by the researchers' intent.

9. Conclusions

The ICTs used in CM (CM) and Maintenance have varied from the intelligent to the mobile agents. However, the emerging ICTs in the domain are the Web technologies, such as the Web Services and the use of the Semantic framework, which are used in the e-maintenance applications. The Social media technologies, i.e. Web 2.0 technologies, are non-existent in the domain of interest, while the use of the mobile devices has been also found, though it is at the rudimentary phase. The domain of CM and Maintenance has clearly gone through various eras, i.e. the DP era, later on the MIS era and SIS era, and currently we can see findings which can be part of the fourth era, namely IS capability as well. In conclusion, the findings show that there are researchers working in all parts of both the three-era model and the IS capability, however there are fewer findings that can be totally acknowledged to be the part of the IS capability. The e-maintenance approach has proved to be a facilitator for the entrance into the IS capability, since it is a comprehensive approach that considers all its important aspects. Though, there is still much more work to be done, since this era is at its infancy stage. The use of the three-era model and IS capability model provides knowledge about the companies' maturity when it comes to their use of the ICTs as well as the purposes for their use. The acquired knowledge from these models is important, since it provides us with invaluable information regarding what the companies should target at, i.e. objectives to accomplish to get into the later eras, what is recommended since their utilisation of the ICTs would be more in line with the existing state of the art solutions resulting in an optimised use of the characteristics that the different ICTs offer. Consequently, the implementation of the Web technologies, such as the Social media technologies, can simplify collaboration and learning aspects that are important for the last era, i.e. IS capability era. Also, the emergent network-based computing over the Internet, i.e. the Cloud computing, promises new ways to handle the Internet-based computing services as well as to provide the company with new possibilities to acquire the latest technology, which needs further research in order to understand how these developments can affect the e-maintenance solutions and the maintenance department with their own specific characteristics. There is, therefore, a need to implement a multidisciplinary research approach for sustainable IS & ICTs in the industry, since that kind of approach would consider the resource level, organisation level as well as the enterprise level of an organisation. Nevertheless, for CM and Maintenance area it would be beneficial with the support of the e-maintenance to reach the last era, since it would lead to optimisation of the IS capabilities resulting in sustainability of the IS and ICTs for the domain of interest. Nevertheless, the different eras discussed in this paper have emerged because of diverse possibilities that the emergent technologies have offered the organisations, which in turn many companies have been forced to consider to be able to stay competitive on the market. Consequently, the emergent ICTs with high impact on the organisations and the market, such as the cloud computing and big data, will take us to a new era, which will provide companies with new possibilities as well as challenges that they will have to consider to be able to keep ahead competition.

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