**e-Maintenance: trends, challenges and opportunities for modern industry**

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**Abstract:** E-Maintenance has upraised growing interest in recent years. Equipment manufacturers seek to provide equipment-related services in an effort to increase their immunity to market variations. Furthermore, both equipment manufacturers and users are paying more attention to issues such as energy-efficiency and sustainability, in parallel with safety, quality and reduced costs. This emerging market landscape has given a boost to research in e-Maintenance, aimed at making more efficient use of resources and engineering assets. However, it seems that manufacturing companies and end users are somewhat uncertain on how to go ahead but also on which are the particular benefits they may gain with the adoption of e-Maintenance technologies. One reason is that various actors in this area of research offer somewhat differing views on the issue. This paper presents a generic view of e-Maintenance and points out both the benefits as well as the hurdles there still exist on the road to support the complete life cycle of a product with e-Maintenance, while providing a critical assessment of the current state of affairs. Based on this discussion, the paper seeks to assess how e-Maintenance will develop within the next five to ten years. Special emphasis is given on how the end users can benefit from e-Maintenance i.e. how radical the change really is and what are the financial implications related to its adoption.

**Keywords:** Maintenance engineering, Monitoring, Sensors, Diagnosis, Software tools

1. **INTRODUCTION**

The awareness of e-Maintenance has grown during the last few years. The motivation for this is twofold. The hardware and software that can facilitate e-Maintenance has developed rapidly and today Internet through wireless networks seems to be offered in numerous places. Simultaneously the manufacturers of machinery are intentionally moving to developing service business for taking care of the machinery they have produced all the way through the complete life cycle of the equipment. For this the manufacturers need tools for taking care of the machinery in a cost-effective way and this is where e-Maintenance can help. E-Maintenance can be considered a technology where information is provided where it is required. On the other hand maintenance is an assignment that is about information when done in an efficient way. In modern maintenance the activities are carried out at most favourable time before breakage and are based on need rather than on periodic servicing schedules. In some references a lot of weight in e-Maintenance is really given to this preventive feature see e.g. Lee (2006). This is not required in order to carry out e-Maintenance but goes hand in hand when the maintenance strategy is enhanced on the road to economically most favourable solution. Lately quite a lot of research has taken place covering various aspects of e-Maintenance. For example the book E-Maintenance (Holmberg et al., 2010) gives a view of results of a large European project Dynamite (Dynamic Decisions in Maintenance, IP017498) and shows the modern development of a variety of aspects of e-Maintenance. This paper tries to go a little further and thus in the subsequent paragraphs the potential growth of the key areas of e-Maintenance are discussed and such aspects as RFID tags, sensors, signal analysis, hand held computers, use of Internet and data, diagnosis and prognosis and economy of maintenance are covered.

2. **RFID TECHNOLOGY**

The RFID technology has existed for some decades, yet it is only during the last ten years that it has started to make an impact on real world applications. Today RFID technology is considered as the most useful way of connecting physical assets with the information technology infrastructure. Therefore it has been used in ICT solutions for engineering asset management and is thus considered a key element in e-Maintenance. The early primary use of RFID technology has been for identification purposes. Avoiding the necessity for line-of-sight, it is a more sensible option, compared to barcodes. In addition, RFID tags can locally store limited information, a feature above all useful for maintenance management. Since the initial applications at Wal-Mart and the US Department of Defence, RFID tags have gained acceptance in Supply Chain Management (Angeles 2005). A noteworthy step in this direction was the acceptance of EPC standards, which enabled greater interoperability of data exchanges from different vendor products. Being the accepted link between the physical and the IT world, they are considered as a key technology that facilitates the computerisation of asset management and the integration with ERP systems. The typical application scenario is that of omnipresent and contextualised information mediation (Spaccapetra et al. 2005). The
technology can also be used for indirect localisation, thus aiding Location Based Services (LBS). Identifying an asset via RFID tags also enables the linking of a specific user to the asset location. Beyond standardisation and early success stories, RFID technology benefitted from the rapid drop in the costs of both tags and tag readers, facilitating investment justification. A more recent trend is the integration of RFID tags with sensing technology (Roy et al. 2010). This is particularly important to e-Maintenance, as in the future it will enable the merging of identification and sensing into simpler to install, operate and manage solutions. The measurements taken are then instantly contextualised, i.e. they are linked to a precise asset, which operates under certain conditions. Coupled with the usage of handheld devices, this level of integration makes the shop floor machinery data universally available to the networked enterprise users. A typical example in this recent trend is the WISP platform, supported by Intel Corporation. WISP integrates sensing and RFID technology, while also taking care of energy efficiency, but incorporating self-power technologies, such as energy harvesting. The wider adoption of RFID technologies in e-Maintenance still faces challenges. Costs should be further reduced. While the integration with the IT infrastructure has become possible, software integration remains an issue. Furthermore, RFID tags are a source of data themselves. The quantity of data generated by tags can grow radically even with modest tag usage within an enterprise. Existing IT infrastructures have not been designed to cope with this level of data and in most cases need to be upgraded to handle the ever increasing information that needs to be managed (Wu et al. 2006). Another challenge is to ensure reliable operation in various operating environments, as RFID operation can suffer from the presence of metal surfaces or liquids (Floerkemeier, C. and Lampe, M. 2004). Thus, an investment in RFID technology does not only need to take into account the acquisition and initial installation costs, but also the costs required to upgrade the organisation’s IT infrastructure. A potential trend is related to the production of the RFID tags. Increasingly, R&D efforts are pointing towards technologies which will enable organisations to produce their own tags. In practice, tags will be produced with technology similar to inkjet printing, making them highly customisable and easy to produce by the end user (Lakafosis et al. 2010). Furthermore, the possibility to integrate also the sensors themselves in such an RFID printing procedure, makes it likely that the technology will become particularly relevant for maintenance management. Although the state-of-the-art is now reaching this level of technological advances, the technology needs to mature further and prove to be reliable and cost efficient in practice for even wider e-Maintenance adoption.

3. SENSORS

Maintenance engineering often employ condition monitoring and data analysis solutions, as key enablers for implementing condition-based maintenance. The sensor technology itself has reached maturity level in the past but is now seeing a significant upgrade towards smart wireless sensing. From simple wireless sensing nodes to advanced implementations incorporating system-on-a-chip (SOC), smart sensing has moved well beyond the data acquisition functionality. This bonds well with the usage of handheld devices, as discussed in the next section. Chiefly, it enables a significant level of data processing to be performed at the lowest possible level, next to the sensing element, taking the burden from the portable device and reducing the data communication requirements to more manageable levels. The key benefit brought by wireless sensing becomes clear when considering that the sensor nodes are now becoming sophisticated computing components with data input and output capabilities which exploit wireless networking protocols, such as WiFi, ZigBee, WirelessHART or industry-grade Bluetooth. From the e-Maintenance perspective, the wireless sensing nodes are becoming smart monitoring agents, capable of performing automated computational and data storing operations, ranging from basic sample filtering to advanced number crunching (Monostori et al. 2006; Moyné 2007). The e-Maintenance vision considers that such wireless sensing components can be exploited and integrated in on line maintenance management systems, insofar as the CMMS can encapsulate at least part of the domain knowledge that is related to condition monitoring, including wear and failure modes modelling, as well as component life prediction. Within such a framework, wireless sensing is likely to become capable of monitoring, modelling but also diagnosing machinery condition, capturing each machine’s individual behaviour, through learning mechanisms. The great advantage is that such sensing infrastructures can be easily be exploited by both back-office staff and systems, but critically also by shop floor staff, who can be empowered to deliver better, more reliable and efficient maintenance services. Through the usage of wireless sensing, it will become also possible to better exploit the mobile actors and workers in the production system, streamlining the generation and delivery of maintenance orders, arising from the ubiquitous knowledge of the actual machinery condition. Indeed, data relevant to equipment maintenance and condition can become transparently available to personnel, via handheld devices, or even via remote servers. The above are key enablers of maintenance services delivery in a much more flexible way, enabling even the execution of maintenance audits by a team of mobile technical staff. From a data processing point of view, an important research direction is how to upgrade the flexibility of monitoring systems to capture individual machinery behaviour, by incorporating learning and self-awareness elements in the sensing nodes to be installed at the monitored equipment. This can be served by embedded novelty and fault detection mechanisms and more research effort should be directed in making such a prospect more practical and efficient (Emmanouilidis and Pistofidis 2010). Following such trends, wireless sensor networks are increasingly installed as alternatives to wired sensing elements. Their key advantages are: a) ease of installation & operation b) scalability c) topology flexibility d) built-in redundancy and thus extremely low sensitivity to sensor faulty behaviour. Currently, wireless sensors have benefitted from the sharp drop in memory, CPU and RF components prices, coupled with more efficient performance. More work will still be needed towards establishing adequate middleware to support easy and flexible deployment of wireless sensing solutions. Another hurdle is their limited battery life. CPU and even more RF operations are energy-costly and need to
be carefully controlled. On one side this can be achieved by software-controlled or network protocol-management energy efficient operation. Yet even more promising is the incorporation of energy harvesting properties into the sensor boards. Recent efforts have been directed towards converting the sensor nodes from passively driven components to power-management or even power generating components. Of particular concern in wireless condition monitoring is to determine when and what to transmit. It makes no sense for a wireless sensor to transmit, if it is not asked to do so or if it has nothing interesting to transmit. Therefore, an emerging research trend is related to embedded-software-driven RF operation. Novelty and fault detection mechanisms, embedded in the sensing nodes, are natural mechanisms to trigger data transmission. Apart from battery life, wireless sensing deployment and applicability needs damage-proof protection. Other problems are related to wireless interference from the environment or by the presence of several other devices, reducing the reliability and effective bandwidth of the deployed network (Conant 2006). More ruggedized enclosures can help in this direction.

4. PREDICTIVE HEALTH MONITORING

In order to use the measured process and condition monitoring signals in an ideal way to support the diagnosis and prognosis phases of e-Maintenance refined signal analysis should be used. In principle all the required features would seem to be obtainable. The processing power of processors has improved and some of the sensors already have this processing ability thus providing information for these analyses. However, in the light of reviews like that of Jardine et al. (2006) it seems that, even though quite a lot of research has taken place and numerous papers about several signal analysis techniques have been published, no essential methods have gained viable success since the introduction of envelope technique in the middle of eighties for monitoring bearing faults (McFadden et al., 1984). In condition monitoring the use of spectrum analysis together with the envelope analysis is the ordinary procedure today presented by most of the condition monitoring systems. The motivation for this is the usefulness of spectrum analysis and the rationality behind it which can without problems be understood by the specialists carrying out condition monitoring with the aid of portable data collectors. The reality is that automatic diagnosis has not turned out to be widespread even though a lot of research has taken place see e.g. Jardine et al. (2006). The usage of spectrum data as the singular evidence for diagnosis means that the end user is dependent on data in frequency domain. For a diagnostic tool to provide something that is truly useful. Based on reviews like Dimla’s (1997) it would look as if many researchers are very inexperienced when they assume that a sophisticated classifier can resolve the problem. If the usage of correct sensors with proper signal analysis techniques is ignored there is no change of realisation since if the basic evidence the classification relies on is of deprived quality there is no way a good classifier could crack this problem. In the future a number of companies are providing services for the machinery they manufacture and thus a lot of data will become available to upkeep condition monitoring. In the following years especially the enriched understanding of wear of the components of the machinery will help in the automation of diagnosis. It can be expected that in the future supplementary process data will be available and also simulation models will be available to provide added information to support diagnosis and prognosis. Due to the difficulty of diagnosis and prognosis of rotating machinery the data mining and classification techniques do not provide sufficient support but they are very useful in spare parts and resources management based on more statistical than physical modelling. It can be anticipated that the ordering of spare parts and their management will in fact become semiautomatic. It is likely to start from the cheaper parts that are used in numbers and then go to the more expensive and rare parts. Up-to-date e-Maintenance solutions could even now carry out all the ordering and work force management automatically but the scenario of things going wrong i.e. sending out wrong orders for parts and work orders in great numbers is ruling out this improvement. However, this process will naturally go further as more understanding is gained from the semiautomatic solutions.

5. DATA AND WEB SERVICES

Quite often the measured data is today saved in hardware specific formats, limiting interoperability and making integration harder. On the other hand, efforts, such as MIMOSA, aim at establishing a standardised data format so that hardware and software integration becomes more straightforward. The MIMOSA organisation (Machinery Information Man-
agagement Open Systems Alliance) is devoted to developing and encouraging the adoption of open information standards for Operations and Maintenance in manufacturing, fleet, and facility environments. For information acquisition processes, MIMOSA provides the standard OSA-CBM (Open Systems Architecture for Condition Based Maintenance), developed to support interoperability through different CBM components. To complement this standard, MIMOSA also offers the standard OSA-EAI (Open Systems Architecture for Enterprise Application Integration), formed to solve the problem of integrating dissimilar applications. OSA-EAI is in fact a large database enclosing hundreds of tables. The MIMOSA schema covers subjects associated to measurements, condition monitoring, diagnosis, prognosis and management of maintenance work orders. Even though MIMOSA is well-documented and supported for implementation, e.g. using an SQL Server, it is not an easy step to start using such a database in a pragmatic way. Moreover it is a challenge to keep the database up to date. Thus, MIMOSA has not achieved deep penetration in market-available solutions. The end users have not so far been motivated to ask for the hardware suppliers to support a common platform and the hardware manufacturers themselves have then considered it better to rely on their own format. The revolution in maintenance policy and the scaling-up of the condition monitoring infrastructure will push for improved and automatic diagnosis, which in turn implies that a huge leap forward in data management has to be taken. The open issues about data format are not limited to condition monitoring, but are also relevant to design data of equipment and process data in automation. In these fields the standardisation effort are much greater. It is somewhat doubtful whether this kind of standards will be the solution. A complementary supportive solution to standards is the development of domain-specific ontologies and semantics. Web-based computing empowers dispersed communication and information storage and on-demand software creation in the form of web-services, thus becoming a powerful computing paradigm for e-Maintenance. The presence of these dispersed services to carry out information analysis, management, work order execution, event data capture, is powerful enabler of e-Maintenance. On the other hand, Semantic Web technologies greatly facilitate information interoperability, by giving meaning (semantics), in a way understandable by computers and enabling easier applications integration (Berners-Lee 2001). Web services, exploiting semantic web concepts can be invoked to provide the requested data in near real time in e-Maintenance. However, companies still use legacy data formats and any upgrade requires significant investments. Ultimately, the adoption of a common data format should be aimed at the complete lifecycle of an asset, making easier its adoption across the complete services chain.

6. PERSONAL DIGITAL ASSISTANT
The use of mobile devices as PDAs and Smart Phones is not frequently related to support the maintenance tasks for several reasons: 1) The cost of PDAs and Smart Phones has been relatively high in case of covering the whole maintenance staff. 2) The maintenance staff is not used to employ these mobile devices. 3) The backend systems do not support the work management. 4) The remarkable financial potential is not understood by the industry. However, a remarkable change can be expected within the near future. The cost of Smart Phones is quickly decreasing and being of highest importance for the manufacturers. Also end users quickly adapt the new possibilities Smart Phones offer i.e. Internet availability everywhere. The result will be that the two main drawbacks on the way to rely on mobile hand held devices while supporting maintenance actions will be quickly disappear. Regarding the third and fourth drawback the trend in manufacturing industry towards providing services for the whole life cycle of their product will mark that the company’s CMMS system has to support the service business. Companies should base their business on historical data which have lots, although sometimes the quality of those hand filled forms is of the type “Machine is broke”, “Fixed the machine”. This means that there will be a really fast leap in manufacturing companies towards using handheld mobile devices for tasks like: 1) Work order management 2) Communication with service center 3) Finding the way to the machine to be maintained 4) Reporting work, availability and location. Even though it is easy to predict the trend it is slightly more difficult to predict the form it will take place. Some of the solutions already exist through Internet connection but the problem is that people do not want to work with mammoth system like the ERP packages that use obscure or unfamiliar terms for the tasks that end user needs. Probably due to the described feature a great number of lightweight solutions will pop up for various purposes and industrial sectors and a middle wear is needed to take care of integration and data management. Today PDAs are to some extent used to support condition monitoring and especially finding out the status of the machines through process parameters and error codes. The difficult question to answer is how will these tasks in e-Maintenance be emerged to the above described work management tasks. If the PDA is used for diagnosis and prognosis it needs a lot of processing power for signal analysis which is not normally available in smart phones. There are basically two other options here either the signal processing will be taken care by smart sensors which then can provide already processed data to the hand held device or the data can be processed through WebServices provided by the Internet connection. However this would mean a lot of very low level communication which does not sound very effective. Thus the most probable trend is the rapid development of smart sensors that can support the handheld computers and then when needed the already processed data from various individual sources can be further analyzed and integrated through the data fusion capability offered by Web Services. On the long run technologies like Virtual Reality (VR) and Augmented Reality (AR) can be expected to help in carrying out maintenance work. Today the current manuals are in the form of figures that tell the maintenance technician how to carry out maintenance. With handheld computer video is an option although the drawback is the amount of work needed to produce that kind of material and thus it will probably never cover maintenance tasks widely. Assuming that there exist 3D models of the machinery in question VR technology could be an option to support carrying out maintenance actions. As the term implies AR technology in principle provides additional information to the real world and in mainte-
nance this could be very beneficial especially when the machinery has very complicated structure. Both VR and AR technologies have been tested in research projects. In order to become popular the challenge is in the production of data i.e. when 3D design models can be automatically used to produce VR and AR material they might become popular since seeing components of machinery to fit into their place like in video is much easier to understand than a set of figures and consequently a person with lesser education could be expected to manage the maintenance tasks.

7. ECONOMICS

Today maintenance is considered as a cost centre rather than a business opportunity. However, maintenance business and the understanding of it are developing. The companies begin to realize that maintenance processes have more margin for optimization than operation has. Financial indicators considering the return of investments (e.g. ROI: Return on Investment, RONA: Return on Net Assets, OEE: Overall Equipment Effectiveness) (EN-15341, 2007) can be a good starting point in order to understand the three main areas of plant productivity: Availability, Quality and Craft effectiveness. The cost efficiency in carrying out the maintenance operations is still high even though the reliability and availability have improved considerably in most companies (AEM 2005). One indicator of this efficiency is the so called ‘Wrench Time’. This indicator gives the impression as part of overall craft effectiveness (Peters 2003) and represents the percentage of time an employee occupies applying physical effort to a tool, equipment, or materials in the execution of assigned work. It is used to define how well-organized the plant is at planning, scheduling and performing work. According to Wireman (2003) a representative wrench time in many organizations in EEUU is of 35%. An increasing number of companies recognize maintenance as a natural way to extend operation and productive processes, and are thus looking for the opportunity of moving towards service business. The main idea is to make them less vulnerable to the market changes. The trend towards services is also part of another trend towards more sustainable business models, with environmental aspects in particular becoming economically significant. This new model denotes also less costs concerning raw materials, energy expenditures and recycling needs as shown by Takata et al (2004). The trend in cost reduction for ICT technologies enables today their use in an increasing number of scenarios. This is also in line with reduction perceived in the price of commodities (Cashin and McDermott-2002) of multiple products that facilitate capture, transmission and analysis of data and information in fast, distributed and economic ways. New standards have appeared that facilitate a way to understand how different technologies may interoperate (Thurston & Lebold, 2001). All this new technology available for maintenance & operations activities is having severe consequences in the way operators may do their work. Many studies (Holmberg et al 2010) show that it is beneficial to take into use e-Maintenance and CBM where even small steps can be economically justified. It is also possible to list a number of progressive effects that can be obviously addressed. First of all, it is known that transformation from corrective to predictive maintenance strategies allows the decrease of breakdown suddenly causing production stoppages and a growth in availability. Whereas condition monitoring systems have conventionally concentrated their benefit on improved safety matching to distinguishing failures before the planned time-based schedule and thus minimizing the risk for abrupt breakdowns, condition based strategies can also increase availability by stretching the maintenance intervals, sometimes far beyond actual maintenance schedules. One of the most central challenges is to perceive how e-Maintenance technologies can help preeminent organizations to surpass 50% of wrench time, by decreasing human-centered activities (unscheduled corrective, time-based preventive, manual inspections...). Important Quality and safety improvements may also be anticipated. Lessening of abrupt breakdowns of machines, especially having high power and speed have a high risk of triggering accidents and this can be avoided. This lessening also affects to unplanned quick overhaul activities, where improvised equipment carried out without appropriate knowledge increases the risk of accidents. Even though the future for e-Maintenance is unblemished, new investment in maintenance or service businesses should be reinforced with more than assumptions, especially if they have an obvious initial cost. However, it is thought-provoking to evaluate the advantage of e-Maintenance systems today. In case of business model alterations (from product to service) no reference points exist to understand the benefits e-Maintenance may bring. In most of the cases direct benchmarking with competitors or third companies, that are implementing similar solutions, is useless. In many companies, the foremost idea is to ‘start from scratch’. This is challenging if there is not a quantifiable indication of the original status nor of the future developments. In these cases, a necessary step is to adapt the necessary KPIs to company characteristics and to follow their advancement. Unfortunately main KPI in companies appear to be related to product reliability or availability, which is limited with respect to direct maintenance costs, where Maintenance may show its benefits. Once KPIs are clear, it is compulsory to define a rational method to analyze what are the most central features to improve concerning the e-Maintenance economics. These analysis (cost-benefit, cost-effectiveness approaches) are beginning to act as strategic tools that permit to integrate, among other, predictive strategies, such as MMME Man-Machine-Maintenance-Economy) model (Al-Najjar, 2010), where strategical changes are revealed in several influence categories, such as direct maintenance costs, investment related bonus/malus ratios, etc. Some other models are more detailed, but require also existing data sources, such as EXAKT (Jardine & Tsang, 2006), which is connected to the data acquisition from mixed sources (i.e. condition data plus reliability data) and may offer a rational way to understand the optimum replacement or repair decision, or, in a strategical level, the suitable examination, repair or replacement period associated to a type of machinery. It is possible to summarize that e-Maintenance is a way to avoid unnecessary tasks and to increase availability, quality and safety. According to Shah & Littlefield (2009) companies best in class have an average 58% of their maintenance tasks based on condition, whereas laggards have only 9%. With an introspective analysis of the company economics, it is possible to achieve high benefits from the incorpora-
tion of e-Maintenance technologies, starting from those oriented to predictive strategies.

8. CONCLUSION

During the last decade we have seen the emergence of e-Maintenance techniques. The main enabling hardware elements of e-Maintenance are the RFID tags, the MEMS sensors together with the PDA. Together with the hardware development the extensive use of Internet and Web Service technology have laid down the new foundation for modern maintenance. Today the use of e-Maintenance is still at infant stage. However, the introduction of e-Maintenance is especially motivated by the changes of strategy of manufacturing industries towards the capability of providing services throughout the life time of the equipment they have manufactured. This step forward will be supported by the hardware improvement but the most significant factor is the availability of new data that can support diagnosis and predictive health monitoring and support to raise them to a level that is of genuine benefit for the maintenance technicians. The progress of new signal analysis techniques joined with simulation models can be the factor that enable a revolution in the prediction of the life time of components of machinery. The technologies are obtainable today and their introduction could be easily justified economically but it will take some time before all the available options will be taken into use. Naturally the success stories of those in the forefront will boost the adoption of new technologies in greater numbers.

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